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AIRCRAFT MEASUREMENTS AND ANALYSIS OF  
SEVERE STORMS: 1975 FIELD EXPERIMENT

FINAL REPORT

NSG-1023; NASA SEVERE STORM SURVEILLANCE PROGRAM

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## ABSTRACT

This Final Report covers the period 7 February 1975 to 31 January 1976 and it represents an overview of the Colorado State University (CSU), Severe Storm Measurement and Analysis Group's (SSMAG) 1975 aircraft measurements in support of the NASA's Severe Storm Surveillance Program (SSSP). Because of the short preparation time allotted to the design, development, instrumentation, and calibration of the aircraft research systems, all three research aircraft were not available initially for the selected storm cases. However, three aircraft and instrumentation systems were completed (two aircraft purchased) within 68 days from the initial funding date (7 Feb. 1975) with all three research aircraft in a operational status by 20 May 1975. By the end of the field operation period (15 June), six severe storm cases had been scheduled by NASA Goddard. Of these six cases, the Queen Air mid-level aircraft was successful in obtaining meaningful measurements on two cases (27 April and 6 May) with two cases (26 April and 30 May) cancelled by NASA because of lack of storm development. The data results indicate that the original concept of a highly mobile research aircraft capability for obtaining detailed measurements of wind, temperature, dew point, etc. near and within specifically designated severe storms is entirely feasible and has been demonstrated for the first time by this program. This program is unique in that it is designed to be highly mobile in order to move to and/or with the developing storm systems to obtain the necessary measurements. Previous programs have all been fixed to a particular location and therefore have had to wait for the storms to come within their network. This latter approach is much too costly in terms of

storms studied per program dollar cost, The present research is designed around a highly mobile aircraft measurements group in order to maximize the storm cases during the field measurements program. It is to be expected that the present research aircraft and mobility capability, given adequate funding lead time, will next severe storm season provide the necessary data base for the programmed storm studies.

## I. Introduction

During the spring and summer of each year, the eastern half of the United States experiences violent squall line and tornadic storms that kill hundreds of people and result in many millions of dollars damage. As the population density in the U.S. increases, the number of deaths and property damage will increase markedly. Consequently, a significant increase in our understanding of severe storms by direct observations is urgently needed to assist the development of adequate ground and/or satellite based warning systems and the design of safe homes and buildings. This information is especially pertinent with respect to the design of potentially hazardous structures such as nuclear power plants and toxic chemical plants or depots.

### A. Project Objectives

The purpose of the present research has been to gain a clearer insight into the severe storm structure and life-cycle by direct cloud penetrations and environmental measurements with three specially instrumented atmospheric research aircraft. This research is a natural extension of our previous storm and analysis programs. The first three sections of this report present an overview and aircraft-instrumentation outline of the CSU program support to the NASA, Severe Storm Surveillance Program (SSSP). The latter sections of (IV-VI) contain specific information on the 1975 Springfield program.

The aircraft measurement program is specifically designed to accomplish the following two-fold objective:

1. Determine from aircraft measurements the storm near-environment circulation and the vertical motion and temperature fields at several

levels from the ground to approximately 40,000 ft, MSL. Three special research aircraft are to be employed; one in the sub-cloud region, one at mid-levels outside the visible convective cell, and another within the cloud above 15,000 ft, MSL. The flight profiles of the three aircraft will provide the necessary measurements of cloud near-environment circulation and in-cloud buoyancy, vertical velocity and updraft slope to further our understanding of the mechanism(s) controlling storm movement (Costen, 1972; Costen, et al., 1974)--in particular the rotating tornado storms which veer to the right of the mean wind (Fujita, 1958).

2. Determine from aircraft measurements the dynamical-thermodynamical properties of the storm updraft-downdraft region in order to formulate a more quantitative descriptive model of severe storm initiation, growth, and dissipation phases. Formulation of such a model will permit mathematical synthesis of a more complete model than presently exists. With these model(s), a systematic study can be made of the storm energy budget and factors which might control storm development and intensity. A primary objective of this cloud modeling research will be to formulate a realistic physical model(s) of the turbulent entrainment-detrainment process. The aircraft turbulence measurements will provide the necessary guidance in the formulation of the mixing process models. The final goal is to develop refined severe storm models which will bring into sharper focus those severe storm-tornado features or characteristics, i.e., tornado cyclone signatures, which can be observed and monitored by satellites.

#### B. Aircraft and Instrumentation Systems

##### 1. Aircraft and Altitude Location

In order to accomplish the desired goals, the Severe Storm Measurement and Analysis Group (SSMAG) has instrumented, calibrated, and deployed

the following three specially equipped atmospheric research aircraft with flight and group support crews:

- (a) McDonnell F-101B severe storm penetration aircraft (15,000-40,000 ft. MSL); Fig. 1
- (b) Beech Queen Air B-80 mid-level environmental aircraft (15,000-25,000 ft. MSL); Fig. 2
- (c) North American (N.A.) T-28 sub-cloud aircraft (sfc - 15,000 ft. MSL); Fig. 3

All aircraft have similar instrumentation systems and sufficient performance to provide extensive overlap in measurement capability near and within the storm cell.

## 2. Instrumentation Systems: AADS-2B-5A

### a. F-101B Severe Storm Penetration Aircraft: AADS-4A

SSMAG has developed several Airborne Atmospheric Data Systems (AADS-3B-4A) for the direct measurements of the three-dimensional velocity field, temperature, and pressure in severe storms between 16,000 to 42,000 ft, MSL. The measurement system is designed so as to be independent of the aircraft sensitivity to atmospheric motions and/or pilot induced motions. The measurement technique (Sinclair, 1969, 1973) requires knowledge of the air motion relative to the airplane ( $V_{a,p}$ ) and the motion of the airplane relative to the ground ( $V_{p,g}$ ) in order to calculate the atmospheric motion with respect to the ground ( $V_{a,g}$ ) i.e., from Figure 4:

$$V_{a,g} = V_{a,p} + V_{p,g}$$

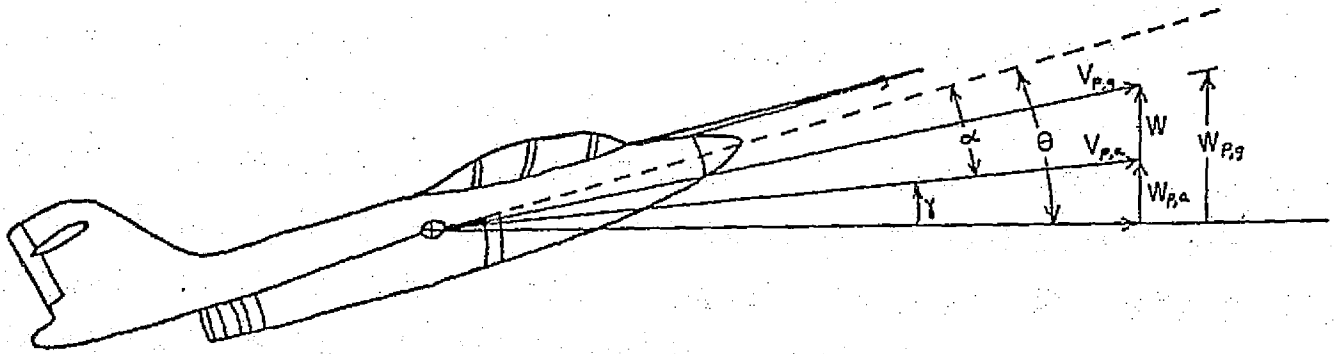


Figure 4: Relationship of Vertical Velocity Measurement System and Aircraft Flight Axes

Using the small angle approximation, the vertical component ( $W_{a,g}$ ) can be expressed as;

$$W_{a,g} = W_{P,g}(0) + V_T \alpha + V_T \beta \phi - V_T \theta + \int_0^t a_z dt + L \dot{\theta}$$

where  $V_T$  is the true air speed;  $\alpha$  the angle of attack,  $\theta$ ,  $\beta$ , and  $\phi$  the pitch, yaw, roll angles, respectively;  $a_z$  the vertical acceleration of the aircraft;  $W_{P,g}(0)$  and vertical motion of the aircraft at time  $t = 0$ ;  $\dot{\theta}$  the pitch rate; and  $L$  the accelerometer displacement from the angle of attack measurement point. The measurement of  $\alpha$  and  $\beta$  are made with lightweight, but durable flow vanes (Figs. 1, 5). The flow vanes and pitot system are mounted on a nose-boom in front of the aircraft to minimize the affects of fuselage induced flow fields. As in all nose-boom designs, the length of the boom is always a compromise between boom natural frequency, size, structural integrity, and complete removal of upwash and pressure errors. The boom natural frequency requirement of 12 Hz and the available aircraft mounting location specified the boom size. Upwash and static pressure errors have been removed by careful tower



fly-by calibrations and aircraft intercomparison flight tests.

Dynamic response characteristics of the vane-pitot tube system were accomplished by programmed pitch-roll flight tests (roller-coaster maneuvers). These calibrations and flight tests indicate that the AADS-4 system have the following mean error bands:

$$\Delta u = \Delta v = \Delta w = \pm 0.5 \text{ msec}^{-1}; \Delta T = \pm 0.3^\circ\text{C}; \Delta P = \pm 0.005 \text{ psi}$$

The pitch ( $\theta$ ), pitch rate ( $\dot{\theta}$ ), roll ( $\phi$ ), and yaw ( $\beta$ ) angles are measured by precision vertical, rate, and heading gyros located in an environmentally controlled temperature chamber in the nose of the aircraft (Fig. 6a, b). Aircraft accelerations are monitored by a three-axis accelerometer system mounted at the aircraft c.g. and the true airspeed is calculated from measurements of total pressure, static pressure, and total temperature. The static temperature and true airspeed are determined by use of the compressible, subsonic flow equations (Sinclair, 1973).

$$\frac{P_t - P_s}{P_s} = (1 + \frac{\gamma - 1}{2} M^2) \frac{\gamma}{\gamma - 1}$$

$$\frac{T_t}{T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

$$V_t = T_t^{1/2} \text{ gR} / (1 + \frac{\gamma - 1}{2})^{1/2}$$

where:  $P_t$  = total pressure;  $P_s$  = static pressure;  $M$  = Mach number;  $T_t$  = total temperature;  $T_s$  = static temperature;  $r$  = recovery factor;  $\gamma$  = ratio of specific heats of air;  $c_p/c_v$ ;  $V_t$  = true airspeed.

Relatively fine structure of the turbulent velocity and temperature spectrum (0.04 to 10 Hz) can be obtained from the twenty channels of data which are recorded on a 1000 character per second, digital, incremental

magnetic tape recorder. The fast response sensors are sampled every 0.02 sec while the slower responding instruments are sampled every 0.04 sec. The AADS-4A systems control and recording center is located in the rear cockpit of the F-101B in front of the flight director (Fig. 7). Eight-pole Butterworth filters are used in the AADS-2, 4 systems to remove data fluctuations with frequencies higher than 10 hz. In addition similar digital filtering is employed in the computer processing of the raw data prior to converting the digital signals to engineering units. This provides an effective filter system for removing nose-boom vibrations errors; internal electronic noise, and aircraft systems noise (Fig. 8).

Since ground research radars are not normally available to determine the location and intensity of cloud reflectivity zones prior to penetration, the F-101B MG-13 fire control radar has been used to provide the necessary radar surveillance of the storm. During this first year of operation it has become even more apparent that without suitable radar probing of the storm prior to penetration only relatively small clouds could be selected for study. We are still in the process of completing the MG-13 modification in order to provide iso-echo contouring and gain selection. The reflectivity contouring capability will provide a better estimate of the location of the high reflectivity core of the storm.

b. Queen Air B-80 Mid-Level Cloud Environment Aircraft: AADS-5A

The B-80 was specifically acquired for the proposed program and it was, therefore, outfitted with a new instrumentation system (AADS-5A) with the same capabilities as the AADS-4A in the F-101B. This is a complete system installation which includes all sensors, interface units, and digital recording system. In addition, five special antennas and a large (450 lb) spherics data system has been installed to support

three additional participating research groups: (1) NASA Goddard severe storm radio emission (3-400MHZ) spherics research, P.I. Dr. David LeVine; (2) NOAA Wave Propagation Laboratory spherics research, P.I. Dr. William Taylor; (3) University of Arizona spherics research, P.I. Dr. Phillip Krider. Because of the B-80's lower altitude flight profile, a doppler radar wind system has been used in place of the F-101B's VLF system. The doppler wind system and the primary DME system provides a dual wind measurement system for higher accuracy and back-up redundancy. While this dual system is not as accurate as an inertial system, it provides horizontal wind measurements every 1-3 km (depending on aircraft type) with an accuracy of approximately  $\pm \text{msec}^{-1}$  at about 10% the cost of the inertial system. Because of the late funding for the program, the DME switching systems are still in the fabrication stage and will not be available until the 1976 spring storm season.

c. N.A. T-28 Sub-Cloud Research Aircraft: AADS-2B-C

Over the past six years we have developed aircraft measurements systems and flight crews that are capable of severe storm sub-cloud flight profiles in the most severe flight environments. In all cases these systems have been installed in military type aircraft that are sufficiently strong to withstand the possible severe turbulence and hail encountered in this region. Considerable experience from previous flight programs indicates that only military type aircraft (stressed to at least +8 to -5 g ultimate) are reasonable choices for the sub-cloud flight regime. The use of business-type twin engine aircraft, which is very prevalent, in the sub-cloud region is so dangerous to warrant this note and to further reiterate the use of highly stressed aircraft for investigations in this region. Simply the loss of the windshield by hail damage in many

of the commercial type single and/or twin engine aircraft would mean the loss of the aircraft and crew. Hail damage received by both the penetration and low-level aircraft in the past substantiate this conclusion. Note that the mid-level B-80 aircraft is VFR and laterally displaced from the visible storm cell by at least 5-10 miles in order to remain outside of the hail zone.

While our present North American T-6 has been a very capable aircraft for probing the sub-cloud region of severe storms, the increased mobility of the present research plan requires a similar but faster aircraft. In order to satisfy the NASA mobility requirements, we purchased a North American T-28 (Hamilton Conversion) aircraft (Fig. 3). This N.A. T-28 is a standard normal category aircraft stressed to +13 g, -8 g that will cruise at over 210 mph and have an on-station research time of approximately 5 hours. We have updated the T-6, AADS-2B system and installed it on the T-28B in the same configuration, i.e., the instrumentation pod-boom system is mounted on the hard points of the right wing. A DME-doppler wind system similar to the B-80 system is also installed, along with a dew point hygrometer and the radio altimeter. All T-28 and B-80 systems have the same accuracy and precision as the F-101B system, and in addition they also have a greater space-time resolution because of lower true airspeeds.

## II. Measurements and Flight Profiles

The aircraft and instrumentation systems have been selected and/or designed to provide detailed wind, temperature, and pressure measurements in three separate severe storm regions. The measurements in these regions are needed to verify existing theories and/or help in the formulation of new physical-numerical cloud models. The three measurement regions are schematically depicted in Figure 9 and are discussed below under separate headings.

### A. Severe Storm Penetration Measurements: F-101B

The aircraft storm penetration tracks usually consist of constant magnetic heading course lines in either crosswind or downwind directions. Essentially, a constant pressure altitude profile is flown outside the storm prior to cloud penetration. During the cloud penetration, a constant attitude profile is flown. From the initial point (I.P.) to the final point (F.P.) a single cloud penetration will normally take a minimum of 3-5 minutes. This profile will allow at least 10 miles of clear air measurements outside of the cloud from the I.P. and the F.P. to the visible cloud boundary. During these penetrations, the AADS-4A will measure and record the three-dimensional wind velocity, temperature, and pressure. The AADS-4A gyro-referenced platform provides aircraft reference data that is used to effectively eliminate errors in the atmospheric measurements due to aircraft roll, pitch, yaw, and accelerations. The complete system has been thoroughly calibrated and flight tested through intercomparison flights with NCAR aircraft and against instrument standards during tower fly-bys.

In general, the results from over 100 penetrations between 20,000 and 40,000 ft. MSL indicate a relatively smooth or non-turbulent environment at a distance 10 miles or more from the visible cloud boundary. Vertical velocities less than  $\pm \text{msec}^{-1}$  are usually present in these regions. As the visible cloud boundary is approached, however, the vertical turbulent component increases rapidly to  $\pm 3\text{--}5 \text{ msec}^{-1}$ . In addition, the penetration measurements of well-organized storms (Sinclair, 1973) indicate that there is, in the mean, a sheath of descending air surrounding the visible cloud boundaries. Within the visible storm boundaries, the vertical velocity of the air (with respect to ground coordinates) reaches peak values of  $+ 40 \text{ msec}^{-1}$ . Temperature anomalies of  $+ 3^{\circ}\text{C}$  to  $+ 10^{\circ}\text{C}$  usually accompany the large positive vertical velocity excursions. In addition, the horizontal gust velocities (i.e., for example  $Aw_{a,g}$ ) appear to be slightly less than the vertical gust velocity component ( $Au_{a,g}$ ) i.e., the turbulent structure is anisotropic. These results are in general agreement with the data obtained by a similarly equipped F-101 aircraft of the NASA Langley Research Center (Steiner and Rhyne, 1962). The updraft region within the storm is of the order of 25 KM in width and appears to be composed of a spectrum of eddy wavelengths which vary from 20 m to  $2 \times 10^4$  m. Within the storm the turbulent energy appears to be separated into three distinct regions: (1) energy source region, (2) quasi-inertial sub-range, and (3) an intermediate region where the steep spectral slope indicates rapid mixing with less buoyant air.

The in-cloud measurements are required in order to support the following NASA-CSU modelling or analysis research:

(1) Quantitative data is needed on the vertical motion and buoyancy fields within the severe storm to support the NASA, Langley (Dr. Robert Costen) modelling program on storm motion.

(2) The measurements are required for internal consistency checks of the severe storm numerical model(s) now being developed at CSU. Because of the lack of a suitable mixing hypothesis or theory, there can be large variations in the shape and magnitude of the vertical motion profile with height in present-day models. Our current research (Sinclair, 1974) indicates that these in-cloud measurements will be extremely useful in the formulation of a realistic mixing parameterization. This must be developed before cloud models will be able to specify a realistic mean and/or turbulent velocity field throughout the storm depth.

(3) Since the magnitude and location of the water-ice particles within the storm are important with respect to storm development and intensity, this information is vital to the cloud modelling research. Some of this information can be deduced from the radar reflectivity data obtained from the penetration aircraft. The radar data is also useful in relating the in-cloud turbulence with the radar reflectivity measurements. This will be a continuation of one of our present efforts to develop remote sensing techniques (based on direct measurements) for observing the storm interior,

#### B. Sub-Cloud Measurements: T-28B

Depending on the visible cloud base, the sub-cloud measurements extend from the ground surface to approximately 15,000 ft. MSL. Higher level measurements are possible, however, since the N.A. T-28 has an operational ceiling of 30,000 ft. MSL. The flight patterns in the sub-cloud layer will be essentially of two types (Figure 9):

(a) Continuous or semi-continuous box patterns at several altitudes are flown to obtain a quantitative picture of the horizontal wind field in the sub-cloud region. The instrumentation system and the flight profiles are designed such that an accurate estimate of the circulation can be deduced from the wind measurements. In addition, these measurements can be used to calculate the convergent-divergent flow across the closed flight tracks and thereby provide an estimate of the mass, momentum, and heat transport near the cloud boundaries. This information is directly related to the storm development time, intensity, and duration.

(b) The sub-cloud flight program is also designed to systematically investigate and "map" the three-dimensional (kinematic-dynamic) structure of the sub-cloud layer. We have obtained these measurements in the past by flying three-dimensional tracks in the updraft as well as in the downdraft region from cloud base to the ground. These multiple-level plots of  $u$ ,  $v$ ,  $w$ ,  $T$ ,  $T_d$ , can be used to construct three-dimensional flow fields of the sub-cloud region. The addition of the DME and doppler wind measurement systems support both the sub-cloud circulation and the updraft-downdraft research.

Our previous experience in flying the sub-cloud updraft region(s) of severe storms and in the analysis of the data suggest the following sub-cloud features;

(a) The updraft region extends to the ground surface with a definite slope toward the direction of storm motion. The updraft is approximately 5-10 miles long and 1-2 miles wide. The most intense region is found in the vicinity of the so-called "scud cloud", and near but displaced below the storm cloud base. In many cases, however, this description can be severely distorted by the occurrence of multiple updraft regions which



all appear to be feeding one central region of the storm above cloud base.

(b) The temperature excesses in the updraft are usually only a few tenths of a degree centigrade and are many times negative indicating considerable mechanical forcing of the flow-field below cloud base. Regardless of the energy source (buoyancy and/or forcing), the cloud base mean vertical velocities are approximately  $5-10 \text{ msec}^{-1}$  with maximum values of  $15-20 \text{ msec}^{-1}$ . Preliminary observations indicate that there may be significant entrainment into the updraft core from the precipitation core when the updraft and downdraft regions are in close proximity during the precipitation stage of the storm life cycle. This mixing may be responsible for the observed negative temperature excesses within the updraft near cloud base.

(c) While the updraft region may appear "smooth" to the aircraft crew, the analysis of the turbulent velocity field shows a similar turbulent energy spectrum as that obtained at higher levels by the F-101B penetration aircraft. Since the upper levels are definitely turbulent, the "smooth" nature of the sub-cloud updraft region may in many cases be a misnomer. In general, however, the picture so far clearly indicates that the cloud base updraft has less turbulent energy at low wavenumbers than that measured at medium or high levels in the storm. The sub-cloud updraft edges, on the other hand, can be as turbulent as the mid and/or upper cloud regions.

#### C. Mid-Level Storm Environmental Measurements: Q.A. B-80

The flight tracks for the mid-level storm environmental measurements are designed such that representative fields of temperature, pressure, humidity and winds are obtained from the visible cloud edge outward to

approximately 25 miles and on all sides of the storm (Figure 9). The nominal flight altitude will be 20,000 ft. MSL but may be modified in order to maintain clearance from the storm and/or to accomplish the most complete coverage of the wind field on a constant pressure surface. The measurement plan is designed to obtain the necessary modelling data for five integrated scientific programs:

(1) NASA Langley (Dr. Robert Costen): This investigation requires at least two levels of wind data from which the circulation around the storm can be calculated. The lower level wind measurements are made by the sub-cloud aircraft (T-28B). The calculated circulation around the storm cell along with the ambient density obtained from the pressure and temperature data is used with other data in the testing of the Costen theory on the right drift of tornado cyclones.

(2) Colorado State University (Dr. Peter C. Sinclair): The mid-level storm measurements are needed in the development of our severe storm entrainment-detrainment model(s). The environmental mean wind, and turbulent velocities, along with the temperature and humidity data, are of interest in our studies of the mass, momentum, and heat transfer across the storm boundaries. These transport components represent the first step in the continuous horizontal mixing process that extends from the outer storm boundary to the center of the updraft core. The horizontal and vertical mixing not only controls the buoyancy of the updraft and hence the development of the storm, but it also acts as a connecting link between the strong horizontal flow of the environment and the intense updraft-downdraft region of the storm. The latter is important with respect to the slope of the updraft axis and the storm's eventual decay.

(3) NASA, Goddard (Dr. David LeVine): This is a piggyback experiment which is investigating the radio emission spectrum from severe storms. It is hypothesized that this spectrum may contain tornado cyclone signatures which will be useful in developing tornado forecasts. The SSMAG of Colorado State University has supported this program by providing the aircraft and personnel to assist the NASA representatives (Georgia Tech.) in the installation and flight operation phases of the program. The program is monitored by Dr. LeVine and will be reported more fully under a separate NASA report.

(4) NOAA, Wave Propagation Laboratory (Mr. William Taylor): This is add-on experiment designed to study the radio emission spectrum at 3.3 mhz. This is a special airborne study of similar work done by Mr. Taylor with ground based receivers. A detailed report of this research will be completed by Mr. Taylor under separate cover to NASA. The SSMAG has also supported this program by providing the aircraft and personnel to ground check and flight test the WPL data system.

(5) University of Arizona, Institute of Atmospheric Physics (Dr. E. Phillip Krider): This research is a second add-on experiment for the study of the near-and far-field lightning spectrum from approximately 150-200 khz. These lightning stroke measurements are analysed (time resolved) for particular features of the received signals. Dr. Krider will provide a detailed report of the results of this research under separate cover to NASA. The SSMAG has also supported this program by providing the aircraft and personnel to ground check and flight test the U of A data system.

### III. Descriptive and Theoretical Severe Storm Models

One of the final goals of the proposed research is the synthesis and formulation of the field measurements into descriptive dynamic-thermodynamic models of the various severe storm stages of initiation, growth, and dissipation. From such models, the distinctive features of the severe storm will become evident, and quantitative estimates can be made of the mass, momentum, heat, and moisture budgets. These descriptive models will provide internal and external cloud boundary conditions that the theoretical models should be able to satisfy using the appropriate initial conditions derived from the field measurements. In this approach, there is a strong interaction between the theoretical models and the field measurement data. This interaction will provide the formulation of more realistic mathematical models of the various severe storm growth stages.

Over the past ten years, numerous attempts have been made to numerically model cumulus type clouds, including deep moist convective cells. The models have been of all three coordinate types, i.e., one-dimensional: Squires and Turner, 1962; Davis, 1967; Weinstein and Davis, 1967; Weinstein, 1969; Davis, et al, 1969; Simpson and Wiggert, 1969; Weinstein, 1970; Ogura and Takahashi, 1971; Danielson et al, 1972; two-dimensional: Malkus and Witt, 1959; Ogura, 1963; Orville and Liu, 1969; Murray, 1970; Takeda, 1971; Schlesinger, 1973a, b and Hane, 1973; three dimensional: Steiner, 1973; and Wilhelmson, 1974. While these cloud models have used various formats to parameterize the microphysics of cloud and rain water, the ice phase, and the entrainment-detrainment process, they have nevertheless been successful in bringing the state-of-the-art from a qualitative realm to one in which the motion and state parameters can be numerically deduced

in both time and space. This success is largely shared by the availability of large, high-speed computing facilities.

On the other hand, even the most sophisticated models of deep moist convection (Danielson, et al, 1972; Hane, 1973 and Wilhelmson, 1974) do not agree with several crucial observations.

For example, in situ severe storm measurements by penetrating aircraft (Sinclair, 1969, 1973) and photographic observations by Fujita (1974) have shown that:

- (1) Maximum vertical velocities as high as  $35\text{--}40 \text{ msec}^{-1}$  have been measured at 9.5-10 km.
- (2) Maximum cloud temperature excesses of  $10^{\circ}\text{--}13^{\circ}\text{C}$  have been measured at 9.5-10 km.
- (3) Overshooting domes from severe storms frequently penetrate many thousands of feet into the stratosphere. This requires a vertical velocity of approximately  $30 \text{ msec}^{-1}$  at tropopause for a 5,000 ft. penetration into the stratosphere.

On the other hand, the numerical models invariably place the updraft maximum of usually  $25\text{--}30 \text{ msec}^{-1}$  at 6-7 km with a maximum temperature excess of approximately  $6^{\circ}\text{--}8^{\circ}\text{C}$ . Although the models are labeled thunderstorms, severe storms, or squall line thunderstorms, they do not at the present develop an updraft region that is supported by the available observations. This lack of agreement is crucial to both the vertical interaction with the stratosphere as well as the space-time variation of the motion fields and their accompanying liquid-solid particle distribution.

These discrepancies are primarily the result of using unrealistic cloud-environment mixing processes. Consequently, we proposed to extend our present modelling efforts to the severe storm situation with special

emphasis on the development of a realistic mixing process. The main emphasis will be to utilize the data from the field measurements to bring into sharper focus the magnitude and the manner in which entrainment enters into the cloud evolutionary process. The aircraft measurements of the three-dimensional velocity and temperature-humidity structure of the updraft-downdraft cores and environment, both below and within the cloud, will provide the necessary data for a direct approximation of the role entrainment plays in the storm development.

Our previous research indicates that one of the important difficulties in a realistic formulation of the mixing (entrainment-detrainment) process for convective clouds of all scales is the lack of knowledge concerning the turbulent flow fields near and within these systems. As a result, we lack a suitable physical model(s) of the mixing process which when incorporated into numerical cloud models will provide an adequate description of the spatial variations of the vertical velocity and temperature distribution near and within the updraft core. For example, the large temperature variations ( $\Delta T = 5^{\circ}\text{--}13^{\circ}\text{C}$ ) and the high altitude vertical velocity maximums (Sinclair, 1973) suggest the development of more suitable mixing techniques than the simple inverse radius parameterizations deduced from fluid plumes and jets. It seems reasonable, therefore, that before a realistic theoretical or physical hypothesis theory can be developed of the mixing process, a better picture of the cloud eddy structure must be synthesized (Sinclair, 1974).

A conceptual picture of the mixing process which takes place, for example, near and within cumulus type clouds requires basic information on the distribution of turbulent eddy intensity and size. Under certain restrictions the turbulent energy field can be visualized in terms of a

continuous field of eddies of varying intensity by power spectrum analysis. With respect to the vertical component only, Fig. 10 shows a number of spectra for both the cloud interior and the clear air outside the visible cloud boundaries. The diagram is a log-log plot of the spectral density vs. wavelength, using an appropriate aircraft mean true air speed. Three different aircraft and data systems were used to obtain the vertical velocity measurements at both cloud base and the upper levels of several severe storms. The Mark III and SNJ aircraft measurements are within the same storm at mean flight levels of approximately 30,000 ft. MSL and 10,500 ft. MSL, respectively.

These spectra, in general, appear to be characteristic of four separate regions that are distinguishable by significant changes in the slope of the spectral curves. Dashed lines bounding the spectral plots represent roughly the slope of the curves within the so-called inertial sub-range (I), the buoyant sub-range (II) and the energy source region for the cloud (III and IV). The longitudinal (u) and lateral (v) velocity spectra indicate that the turbulence is not isotropic as might be expected from the large buoyant energy input in the vertical direction. The anisotropy is most apparent at the long wavelengths where the energy source is located. While the exact specification of the various sub-range spectral slopes and their wavelength boundaries appears impossible due to the space-time variations of the phenomena, the existence of a distinct transition zone (sub-range II) between the energy source region and the inertial sub-range suggests a wave number region where significant turbulent mixing takes place. That is, it seems probable that the large shearing stresses generated at the boundaries of the energy source region act to generate eddies of sub-range II size which in turn erode away the temperature or

density anomalies of the source region eddies. Thus, the generation of large temperature anomalies within the updraft core of a cloud or severe storm results in a self-destructive mechanism through the generation of eddies of sub-range II size which result in the turbulent transfer of heat and momentum from the energy source range to the inertial sub-range. These eddies in sub-range II have their density fluctuations effectively neutralized during the mixing process, and hence the buoyancy contribution to the eddy kinetic energy in this range decreases rapidly. Sub-range II merges with the inertial sub-range (I) for eddy sizes too small to exhibit significant density fluctuations. This conceptual model suggests, that the rapid decay or annihilation of the eddy kinetic energy in sub-range II is associated with a major heat (also mass and momentum) transfer mechanism between the major updraft and the updraft environment. Consequently, the primary cloud mixing processes may be confined within a narrow wavenumber range. This information is now being used to formulate a mixing hypothesis that can be realistically parameterized for model incorporation. Since the mixing process controls the cloud growth rate(s) and the maximum vertical extent and intensity, it is imperative that this process be modeled more exactly from physical interpretation of in situ measurements. The results of this research should have relevance to the question of why certain clouds develop into severe storms or tornado cyclones.

In addition to the modelling of cloud processes, we are currently working with Dr. Costen (NASA, Langley) on the verification of his theory concerning the motion and structure of severe local storms. Fujita (1958) had observed that while most thunderstorms move with the mean environmental wind, those that rotate (tornado cyclones) tend to veer at angles of  $20^\circ$



to  $60^\circ$  to the right of the mean wind. The theory is based on the assumption that the axis of the buoyant updraft of the tornado cyclone is tilted from the vertical. There is, therefore, a component of the buoyant force normal to the updraft axis, and this component is balanced by the Magnus force generated by the drift of the cyclone.

We have been cooperating in this research through our aircraft measurements program of severe storms. The severe storm measurements by the F-101B penetration aircraft have shown that the updraft core rises essentially undiluted throughout much of the cloud depth (Sinclair, 1973). This temperature data along with the vertical velocity and updraft size information is required in the calculation of the transverse buoyant force. In addition, the circulation of the mean environmental wind around the storm is also required to calculate the Magnus force. This proposal has been specifically designed to provide the necessary in situ airborne measurements from three aircraft for verification of this storm drift theory. A positive verification of the theory may have potential application to satellite detection of severe storms and development of a satellite-based tornado warning system.

#### IV. Aircraft Deployment

Normally the SSSP Director would provide a 48 hr. alert for possible movement of the aircraft to an initial staging area. This 48 hr. alert was primarily for the purpose of flight preparation and field logistics planning for the specific area of operation. Because of the tenuous nature of the 48 hr. alert all aircraft were held at the home base. A second alert at 24 hr. prior to anticipated activity was used to move the aircraft and crews to the best forward staging area. Because of aircraft weight restrictions due to instrumentation load and on-board flight crews, ground support personnel were sometimes moved to (or close to) the selected staging area by commercial airline) After arrival at this initial staging area, the aircraft could in some cases be repositioned for more optimum locations for the anticipated storm flights. The 1975 SSSP staging areas and enroute tracks of each storm case are shown in Figure 11. These alerting procedures, as originally envisioned, were well thought out and appeared to present no anticipated problems. However, the decision to move at the 24 hr. alert time should be modified to allow more time for aircraft, crew, and logistics support. In several cases the alert came late in the day and the decision to move the following morning meant that the storm flights were made on the same day as the aircraft staging day. This resulted in flight crews exceeding authorized daily flight hour limits and missing meals (lunches). Also, the arrival back at the final staging base after 2000 LST, meant that crew rest would be insufficient for scheduling a second storm flight day. Several easily incorporated improvements in the present alert plans and communication-vectoring procedures for next year are discussed in the Conclusions

Section (V). In general, however, we feel that this first operational year has shown that the initial mobility concept is valid and can be fully exploited to provide the necessary severe storm data that fixed location programs cannot provide in a reasonable time limit.

## V. Severe Storm Cases

### A. 24 April: St. Louis, Missouri Case

On the morning of 24 April the Q.A., T-28, and F-101B deployed to Tinker AFB, Okla. for an afternoon mission in the St. Louis area. The Q.A. and T-28 made a quick turn around at Tinker AFB (flight crews missed lunch) and proceeded NE to intercept a squall line moving through Missouri. The Q.A. chased this squall line almost to St. Louis and had little success in obtaining data that could be referred to ground coordinates. A minor fault in the aircraft positioning system negated further analysis of the meager data obtained after the long chase of the rapidly moving squall line. The T-28 flying at a lower altitude was never able to reach the intended squall line area because of lack of proper navigational aids supplied by the high flying aircraft and also due to intervening severe storm systems. The F-101B was held at Tinker AFB because of mechanical problems. In retrospect, the alert timing was not sufficient (less than 8 hrs) to move three aircraft from Buckley Air National Guard Base (BANG) to Tinker AFB, refuel, and chase after a fast moving squall line 350 miles to the NE. As a result, the flight crews were on duty in excess of 12 hrs. with only time for one meal. However, this was also the first field experiment of the program, and as a result these initial problems were quickly addressed and corrected during the following field exercises.

### B. 26 April: Goodland, Kansas Case

On the 26th of April a tornado watch area was forecast for the Goodland, Kansas area by the NOAA/SSFC. The Q.A. was flown on the morning of the 26th to Goodland while the F-101B returned to BANG from Tinker AFB,

because of runway length requirements, to stand-by for the afternoon flights. The T-28 was not able to participate because of a malfunction in the doppler wind system. The F-101B and Q.A. stood by the entire day but no severe weather (not even a cloud) developed in the tornado watch area. The Q.A. returned to BANG early in the evening of the 26th.

C. 27 April: Amarillo, Texas Case:

1. Synoptic Weather Situation

A 988 mb low pressure center was located in extreme southwestern Nebraska by 0000Z (1800 CST), Fig. 12. A cold front extended southward from the low center along the eastern border of the Texas panhandle with a secondary trough line extending southwestward from the low through Colorado and New Mexico. Ahead of the cold front, strong northerly advection of warm-moist air was taking place. Behind the front to the west the air was warm and dry, creating a large moisture and stability contrast across the frontal zone. The surface low pressure center and associated frontal system was supported by a deep trough aloft. The 500 mb chart for 28 April (0000 Z), Fig. 13 shows the trough line extending southward from the low center in Montana through Wyoming, Colorado and New Mexico. Ahead of the trough line the southwest flow reached a maximum of at least 80 knts at Amarillo, Texas. Note also the cooler temperatures to the east of the trough line.

Approximately seven hours earlier and closer to the time of the Queen Air Measurements, a severe squall line had developed ahead of the cold front as shown on the Radar Chart of 27 April 1975 (1935 Z), Fig. 14. This squall line began its initial development earlier during the morning of the 27th as observed by the flight crews of the F-101B and Q.A. during the aircraft deployment from Denver to Amarillo. At the time of the Q.A.

measurements, the flight tracks were around a large cell that was part of this line but slightly displaced to the east of the radar depiction of the line. Note the red circled location on Fig. 14. These cells were considered severe with radar tops shown to 50,000 ft. MSL (Fig. 14). The visible tops were consequently at least 53,000-58,000 ft. MSL.

## 2. Aircraft Wind Measurements

Only the Q.A. was able to obtain data on the severe storm case since the T-28 was in a DI status (Table 3) due to the doppler repair at the factory. The F-101B was forced to return prematurely from the selected storm cell because of a tape recorder malfunction. The Q.A. flight tracks and averaged (approx, 40 sec) wind velocity data are shown in Figs. 15 and 16. Figure 16 has been copied over a FAA Sectional Chart for easier geographical location of the cloud and aircraft tracks. The reproductions of the Sectional Charts are of low grade because of the heavy use of coloring on the originals. The wind data shows the general southwesterly flow on both sides of the cloud. Note, however, that the flow is decidedly much more southerly along the southwestern side of the cloud. That is, from the I.P. (1654 CST) to approximately (1714 CST), the wind direction was usually 220 to 230 degrees at 60-70 knts. The turn point times in CST are shown in brackets at the turn points. From (1714-1684 CST), the wind backed from 220 degrees to less than 180 degrees with a speed increase to 95.4 knts at approximately 1725 CST. Closely after this time the tape recorder failed and the remaining winds were calculated from visually read doppler data and crew notes. Consequently they were spaced unevenly around the track and correspond more closely to point winds rather than averaged winds as shown on the first part of the flight. Because of the single flight track around the cloud and the sparse data after tape

recorder failure, it is impossible to depict the flow by streamline analysis or specify convergent-divergent areas. The southerly flow along the southwest flank of the cloud does suggest some blockage of the environmental wind flow in this area and subsequent convergent flow further to the north. It is in this southerly flow on the southwestern side of the cloud that the average wind speed reaches a maximum of 95.4 knts. Note also that the flow appears to veer toward a more westerly flow at the southern end of the cell indicating flow around the cloud in this region. Downwind of the cloud, wind speeds have decreased and are generally less than 55 knts.

The wind data, as well as the temperature and dew point data, are computer tabulated from the basic data as five (5) second averages (Table 1). Each page represents a separate leg of the flight track around the cloud (Fig. 15). The column headings in Table 1 are defined as follows;

1, Flight Leg Number: Number in upper right hand corner depicts the flight leg numbered in sequence from the I.P. to the E.P. Each leg represents a straight line track over the ground.

2, Time: (a) T.R.  $\equiv$  Tape recorder time in increments of five seconds.

(b) R.T.  $\equiv$  Real time (Z) in increments of tenths of a minute. Note this means that some succeeding times are the same although five seconds may have elapsed.

3. Wind Velocity: (a) U and V are the longitudinal and lateral wind components (Knts) with respect to the

aircraft coordinate axes.

(b)  $V_H$  is the wind speed (Knts) and WIND is the wind direction in degrees.

4. Dew Point: Direct measure of the dew point is °C from the Cambridge hygrometer.

5. Temperature: Static temperature in °K from the Rosemount total temperature sensor. Static temperature is calculated using the compressible, sub-sonic flow equations.

6. Altitude: Aircraft altitude in meters (m) above mean sea level.

Note that the first and last line on each data sheet may contain an error due to aircraft turning and tape recorder adjustments.

### 3. Aircraft Temperature and Dew Point Measurement

Simultaneous measurements of temperature ( $T$ ) and dew point ( $T_d$ ) were recorded with the doppler wind data. In general, the temperature and dew point varied by small amounts from  $T = 270^\circ \pm 1^\circ \text{ K}$  and  $T_d = -15^\circ \pm 1^\circ \text{ C}$ . However, there are a number of significant variations in both parameters that are worthy of note.

For example, after R.T. = 1663.8 there are numerous, large fluctuations in the temperatures as depicted in some cases by the checks to the right of the temperatures. In a few cases there also appear to be simultaneous fluctuations in the dew points. These large temperature fluctuations are certainly not real. They appear to have been associated with the intermittent breakdown of a temperature amplifier component and/or aircraft RF transmitter interference. The problem has been eliminated by the replacement of the amplifier with a matched Rosemount unit that is



specifically designed for the temperature sensor and is shielded from RF noise. The Rosemount amplifier purchase and delivery was delayed because of the late receipt of the NASA project funds to Colorado State University. It is anticipated that these data along with more complete data from multiple tracks planned for next year will provide sufficient data for satellite measurement comparisons and severe storm modelling inputs.

D. 6 May: SE Kansas Case

1. Synoptic Weather Situation

The May 7, 0000Z surface chart showed a rather complicated system of fronts extending southward from a 990 mb, low pressure center located on the extreme eastern Wyoming-Montana border (Fig. 17). The primary occluded frontal system had its associated cold frontal system on the Kansas, Missouri, and Oklahoma common borders. Since the map time is for 0000 Z, the aircraft measurements taken between 2100-2200 Z represent pre-cold frontal conditions associated with the observed squall line. Note the measurements were taken at the red cross location which would have been east of the frontal-squall line system between 2100-2200 Z. Two warm frontal systems extend eastward from the primary cold front becoming stationary systems within the high pressure area to the east. A secondary cold front extended southward from the low center through Nebraska, Kansas, Oklahoma, Texas, and New Mexico. This complicated surface frontal pattern did not present as clear a cut case, as on 27 April, of warm, moist southerly advection in the squall line area with warm, dry air to the west of the cold front. Part of this lack of contrast is due to the NWS placement of the primary cold front slightly too far to the east. It appears that the cold front zone of

discontinuity should be moved slightly to the west over the surface stations of Topeka, Chanute (Kansas) and Tulsa, McAlester (Okla.). This analysis would then separate air behind the cold front with dew points of 45°-50° C from moist air ahead of the front with dew points of approximately 65°-70° C.

The upper level 500 mb chart for 7 May 1975 at 0000 Z time (Fig. 18) showed a closed low pressure system centered over Wyoming with the cold air located to the southwest over the four corners area (Utah, Colorado, New Mexico, Arizona). At the time of the aircraft measurements (2116Z), the data is representative of the high pressure ridge region east of the low pressure center (ref. red cross on 500 mb chart). From the wind data it is estimated that winds at this level (approx. 5,700 m) at the time of the aircraft measurements were approximately 220°-240° at 35-45 knts.

Approximately five hours earlier and closer in time to the Queen Air measurements, a severe squall line had developed ahead of the cold front as shown on the 1935Z radar chart of 6 May 1975 (Fig. 19). At this time, radar cloud tops reached 50,000 ft. MSL in the near vicinity of the Q.A. measurements. At the time of the Q.A. measurements, part of the squall line had dissipated to the south producing a gap which allowed a horseshoe type pattern around the southern end of the squall line. The measurements were taken at the location shown by the red circle-cross on Fig. 19. It is important to note that this particular mission was staged out of McConnell AFB (Wichita, Kansas) which is to the west of the squall line. Under these conditions it is usually difficult to penetrate the line even in the suspected "soft" spots indicated by the aircraft radar. As a result the racetrack pattern on one side of the squall line must be employed. As indicated previously this was fortunately

not the case on 6 May, however, this situation emphasizes the critical timing requirements of the aircraft deployment and the calculation of squall line position and translation speed which are necessary to optimize the flight pattern(s).

## 2. Aircraft Wind Measurements

The Q.A. flight tracks around the south end of the major squall-line are shown in Fig. 20. The averaged (approx. 17 sec) wind velocity data are superimposed on the tracks with real times (Z) shown at the turn points. The position and orientation of the squall-line were obtained and plotted independently from the Q.A. wind measurements. Both Q.A. and Learjet navigation data were used to position the squall line location. It is evident that this squall line position agrees very well with the derived doppler wind measurements. That is, there is a distinct wind shift on either side of the turn point at 2123Z which also marks the center line of the squall-line. Also, at this time the aircraft experienced moderate turbulence as the squall-line axis was penetrated. In general, the wind data at the southern end of the squall-line seems to indicate that there is anti-cyclonic flow to the west of the squall-line with cyclonic curvature of the wind flow to the east. The consistency of the doppler wind data is evident at the cross-over point of two flight tracks near 2141.6Z time. The wind direction difference at this point between 2123.5 Z to 2141.6Z was less than 15 deg. with the wind speed essentially constant. Some variation is to be expected, however, because of the squall-line position and the building cumulus in the flight track area. The wind measurements along the west side of the squall-line average approximately  $220^{\circ}$ - $230^{\circ}$  at 35-50 knts which is very close to the synoptic wind velocities quoted earlier.

While the wind data appear quite consistent and reasonable, the tape recorder failure at 2157,5 Z negated obtaining multiple flight tracks at one altitude from which a wind field could be drawn. Several more parallel, but displaced, flight tracks were anticipated in order to obtain this coverage at this initial altitude of approximately 4750 m. A second altitude set of flight tracks had also been planned for an altitude of 5350 m in order to obtain the variation in circulation around the squall line with altitude. This type of coverage is again planned for next year when we will have greater tape recorder reliability.

As in the 27 April, Amarillo, Texas Case, the wind data, as well as the temperature and dew point data, are computer tabulated from the basic data as five (5) second averages (Table 2). Each page represents a separate leg of the flight track around the squall line (Fig. 20). The column headings in Table 2 are the same as those of Table 1.

### 3. Aircraft Temperature and Dew Point Measurements

The temperature variations along all of the flight tracks were very small, amounting to  $268^{\circ} \pm 1^{\circ}\text{K}$ . Maximum altitude variations along the flight tracks amounted to approximately  $\pm 40$  m from a mean altitude of about 4780m. Spurious temperature oscillations appeared to have occurred in only one instance near 2132,6Z. This temperature fluctuation as well as the similar ones on the 27th of April storm case have been eliminated as indicated earlier by the addition of a matched amplifier to the Rosemount temperature sensor. The dew point variations were however larger than on the 27 April storm case. The dew point fluctuated between  $-14,1^{\circ}\text{C}$  to  $-21,7^{\circ}\text{C}$  with successive changes in the average values of as high as  $2,6^{\circ}\text{C}$ . In general, however, these fluctuations were due to vertical moisture transport by small cumulus whose tops were near the

aircraft flight altitude such as indicated at: 2126.2Z, 2137.8Z, and 2142.9Z. Drier air appeared to be located on the west side of the squall-line on the first leg (2116.9-2123Z) and on the fifth and sixth legs from approximately 2146Z to 2152Z. On the last leg (#7), the dew points indicated slightly greater moisture to the north and west of the southern end of the squall-line. However, it is important to note that these dry and moist areas were not continuous regions, but were sporadic or characteristic of individual "pockets" of dry and moist air. Consequently, an analysis of the dew point data results in an extremely erratic moisture pattern. Again, multiple flight tracks spaced further apart may help to improve the analysis.

#### E. 29 May: Northern Texas Case

All three research aircraft (Q.A., T-28, F-101B) were grounded in the Denver area because of a severe snow storm throughout most of the state of Colorado. The airport runways received at least 6-8 inches of snow and were not cleared until late in the afternoon of the 29th. Consequently, the aircraft were unable to reach the severe storm system that developed in northern Texas. All three aircraft were on a UDI status (Table 3) as of 20 May.

#### F. 30 May: Joplin, Missouri Case

Early on the morning of the 30th, all three aircraft departed BANG for Tinker AFB for severe storm flights in the Kansas-Missouri area later in the day. The aircraft arrived Tinker AFB by 1750Z. After refueling the Q.A. and T-28 departed Tinker AFB for Joplin, Missouri in order to be in a better position to intercept the squall-line. The F-101B was held at Tinker because of the speed at which it could reach the research area. By 2130Z the Q.A. and T-28 were advised by Dr. Sinclair to proceed

to an area 150-200 miles northeast of Joplin to intercept the squall-line. The aircraft departed Joplin at 2215Z for the Vichy, Mo, area. However, the squall-line failed to develop and intensify as forecast and Dr. Shenk cancelled the entire field experiment at 2300Z. No research data was obtained and the aircraft returned to Tinker AFB by 2350Z. All three aircraft returned to BANG or Fort Collins on the 31st by 2100Z. From 31 May to 15 June all aircraft and instrumentation systems were in a UAI status (Table 3). However, no storms or storm systems developed and the field portion of the program was terminated on 15 June.

## VI. Conclusions

### A. Significant Results

Although previously mentioned, the primary results of this first year of the Severe Storm Surveillance Program by the CSU/SSMAG can be briefly stated as follows:

1. Within 68 days from receipt of contract funding, two aircraft were purchased, modified, and instrumented with new equipment for sub-cloud (North American T-28) and mid-cloud (Queen Air B80) severe storm measurements. The Q.A. research aircraft was not only modified to carry the CSU/SSMAG research system but it also required five external antenna installations and a large cabin data system installation for the NASA Goddard spherics experiment (Dr. D. LeVine), U of A spherics experiment (Dr. E. P. Krider), and the NASA spherics experiment (Mr. W. Taylor). In addition, a third research aircraft, the F-101B penetration aircraft, was prepared and calibrated for the spring storm season.

2. A new concept in aircraft deployment for severe storm research was developed and successfully tested. Near the end of the field program this unique mobility concept appeared to be fully developed as all three aircraft were operational and in the specified storm research areas at the desired time. The aircraft and instrumentation status or operational readiness for the preparation period and the field experiments is outlined in Table 3. This particular operational capability is critical in that it involves the research aircraft, the flight and ground crews, the logistics of long distance moves, and the close coordination with the FAA for air traffic control. We also believe the success of this aspect of the present SSSP will provide a sound basis for the planning of future (1980) programs such as SESAME.

3. The data obtained this year by the Q.A. mid-level aircraft indicates that the present systems (temperature, pressure, dew-point, wind, etc.) are adequate for the project design. The doppler (APN/153V) wind data has shown that it is a satisfactory and low cost alternative to the more expensive INS systems. In addition, three well-instrumented atmospheric research aircraft are now available for next year's field program. All aircraft, personnel, and support systems can be ready for severe storm deployment alert by 15 March 1977 provided funding reaches CSU not later than 1 Feb. 1977. It is to be expected that this present research aircraft and mobility capability, given adequate funding lead-time next year, will provide the necessary data base for the programmed storm studies.

#### B. Improvements Needed for the 1977 Severe Storm Season.

1. A strict adherence to the 48 hr. alert schedule is necessary in order to deploy the three aircraft to the final forward staging area. In the past we have reacted to an alert of only 24 hrs which left less than 12 hrs to move the aircraft through successive staging points. In order to provide the maximum flexibility in selection of the foremost staging area, we plan to deploy to Tinker AFB approximately 24-48 hrs prior to the normal NASA alert.

2. Considerable improvement in the field communications is desirable in order to keep the sometimes widely dispersed aircraft and crews informed of the deployment schedule. This year we experienced some difficulty in reaching the Project Director or his assistant when CSU aircraft were at a different airbase than were the Learjets. Also, ground communications (ARINC) with the Learjets during the storm flights was not always possible, and hence the launch schedule of the F-101B was sometimes in question.



These communication gaps could be completely or partially eliminated by requiring that the Learjets land and deploy from the same airfields used by the CSU aircraft. Note the CSU, F-101B requires that we usually use military airbases. This would not only improve the daily flight scheduling but would also permit the establishment of a debriefing meeting immediately after the individual storm flights when the information is fresh in the minds of the crews.

4. In addition to the air-to-ground communication problems with the Learjets, we will need to improve the Learjet vectoring of the CSU aircraft to the selected storm cell. Last season the Learjet observers were selecting Vortac for navigation fixes from their high altitude charts. Since these Vortac were invariably beyond the line-of-sight range of the other aircraft, especially the low altitude T-28 aircraft, it is suggested that the Learjets carry a complete supplement of Low Altitude Charts for use in establishing optimum vectors to the storm cell for the other aircraft.

5. In order to improve the correlation of the aircraft data from all aircraft, it is suggested that all aircraft use Greenwich (Zulu) time for time hacks, data notations, and tape recorder time base.

6. To provide greater reliability in the wind measuring systems, a back-up doppler wind system (APN/153V) is needed for the Q.A. and/or the T-28. Purchase cost for a used-reconditioned unit is approximately \$19,500. This is relatively a small cost considering the loss in data because of a unit malfunction while in the field.

7. Because of the rapid mobility requirements and the necessity of field maintenance support for the three aircraft and the instrumentation systems, we have developed fly-away kits for each aircraft and data

system. These kits, because of the heavy equipment already aboard the aircraft, cannot be carried totally or partially on either research aircraft. Consequently, we propose the use of a Cessna turbo 207 type aircraft to transport all support equipment to the forward staging area. This aircraft is already in our inventory and is capable of carrying a useful load (including full fuel) of approximately 1000 lbs. As a result we will be able to transport on a timely basis all the necessary support equipment and personnel. In the past it has been necessary to have the aircraft mechanic follow the aircraft using scheduled airlines. This of course made it very difficult at times for the maintenance personnel to keep up with the aircraft which are based at military fields.

8. As indicated previously the funding date, as determined by the day that funds reach CSU, is very critical with respect to our efforts in meeting a specific start date. That is, funding must reach CSU not later than 1 February in order to make a 15 March start date realistic.

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## VIII. Personnel

Principal Investigator: Peter C. Sinclair, Associate Professor of Atmospheric Science, holds a B.S. degree in Meteorology from the University of Washington, and M.S. degree from the University of California at Los Angeles, and Ph.D. degree from the University of Arizona, Tucson, Arizona. Experience: Research Assistant, Department of Meteorology, University of Washington, Micrometeorology and instrumentation, 1950-1952; USAF Weather Officer, Duty Forecaster and Special Projects Officer in charge of weather research projects for Weather Det. 6-8, McClellan AFB, California, 1952-1956; Research Assistant, Institute of Geophysics, UCLA, large-scale dynamics, 1956-1959; Research Assistant, Institute of Atmospheric Physics, University of Arizona, theoretical and experimental studies of desert convection, mobile ground and aircraft instrumentation, 1959-1965; Assistant Professor of Atmospheric Science, Colorado State University, aircraft and theoretical investigations of severe storms, weather (hailstorm) modification, and aircraft cloud physics instrumentation, 1966-1969; Associate Professor of Atmospheric Science, Colorado State University, 1969-present. Consultant: University of California Lawrence Livermore Radiation Laboratory. Member: American Meteorological Society, American Geophysical Union, American Association for the Advancement of Science, and Sigma Xi, power and sail plane pilot.

Publications:

- Sinclair, P. C., 1964: Some preliminary dust devil measurements. Monthly Weather Review, Vol. 92, No. 8, August.
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- Sinclair, P. C., 1967: Facilities for experimental research in atmospheric science: Design of an atmospheric simulation wind tunnel. Final report to NSF, November.
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Atmospheric Research Pilot - Queen Air. Gilbert L. Summers.  
Plan and execute aircraft atmospheric research missions. Assist in preparation of aircraft for research program.

Education: M.A. George Washington University  
B.A. University of Colorado

Experience: 1973-1975 - Atmospheric Research pilot, National Center for Atmospheric Research; 1972-1973 - Chairman, Flight Technology, Embry-Riddle Aeronautical University; 1970-1972 - Assistant Chairman, Flight Technology, Purdue University. 1946-1970 - Naval Aviator, various types of duties including aircraft research and development and jet carrier squadrons. Approximately 7,000 pilot hours.

Qualifications: FAA Airline Transport Pilot, multi-engine land and sea, single engine land with DC-3 and DC-4 type ratings. Flight instructor, airplane-single and multi-engine land and sea - and instrument. Advanced ground and instrument ground instructor.

Atmospheric Research Pilot - T-28. David J. Younkin.

Education: 193 quarter hours towards a degree in Physical Science with a minor in Business Management - Colorado State University.

Experience: 1971-1975 - involved in weather research for the National Center for Atmospheric Research which included sail plane towing and cloud seeding; 1966-1971 and again in 1974 - contracted with CSU to provide an aircraft and administer and aviation activities associated with their thunderstorm research and weather modification program; 1965-1966 - leased an aircraft to Sky Harbor Air Service and flew 1100 hours as a bush air taxi pilot.

Qualifications: Since 1953 has accumulated 5300 total flying hours of which 600 are weather modification hours; has flown approximately 40 different types of aircraft. Mr. Younkin has owned and administered a pilot school, charter service and speciality flying (aerial photography, aerial advertising). Ratings: private, commercial, CFIA, multi-engine and instrumen'.

AVTEST Engineering, Inc.: J. A. Lucey. AVTEST Engineering test pilot instrumented F-101B storm penetration aircraft and will act as a consultant on storm penetration procedures and associated engineering systems. Mr. Lucey has an extensive background in research and development flight test, plus recent experience in tactical fighter systems and ordnance deliveries, including two combat tours in South Vietnam. He is a graduate of the USAF Experimental Test Pilot School and has over six years of engineering flight test experience in jet fighter aircraft while in the USAF. During this period, he became the first pilot in the history of aviation to penetrate fully developed thunderstorms at supersonic speeds, making penetrations at speeds in excess of 1300 mph (1.9 mach). Among the more than 65 types of aircraft he has flown are the F-106, F-105, F-104, F-102, F-101 and F-100. He was a Command Pilot

in the USAF and has logged more than 5500 hours of flying time. During the past six years, Mr. Lucey has flown all of the severe storm penetrations in northeastern Colorado and Oklahoma for the CSU severe storms group (SSMAG).

Principal Research Technician and Data Analyst. G. Edelen. Programmer/analyst, computer systems technician. Experience: Naval Electronics School, Great Lakes, Illinois; Naval Data Systems and Communication System School, Vallejo, California. Completed numerous and various computer courses in job control, system operation, and programming. Maintained and operated various real time computer systems aboard Naval Aircraft Carriers; 1963-1967. Programmer/analyst, Naval Station, San Diego, California; programming, operation supervisor for AN/UYK-5V computer system; 1967-1969. Programmer/analyst, Colorado State University; planning and programming for the integration of various computers and data handling devices into larger total systems. Provides scientific programming of all hail project data from aircraft and radar sources and computer programming and data analysis of cloud models program, 1969-present.

Principal Electronics Specialist. R. Hill. Supervisor/electronics technician airborne meteorological data collection systems. Experience: 1965-1966 - USN Gun and Missile Fire Control schools Bainbridge, Maryland and Dam Neck, Virginia 55 weeks. Basic electronics through surface to air guided missile systems. 1966-1969 aboard ship performing missile system and missile maintenance. Telemetry system repair and maintenance. 1969-1970 supervisory maintenance in fire control systems. 1970-1973 Colorado State University. Worked in stream flow studies and wind tunnels. Buildup of weather data collection systems. CO<sub>2</sub> laser wind studies, radar modifications for meteorological studies, calibration of precision test equipment and pressure transducers. 1973-1975 Western Scientific Services Inc., buildup and installation of earth resource transmitting systems data collection platforms, soil monitor systems, air quality monitoring systems for power plants. Partial design, buildup, checkout of microprocessor remote data collection systems, and airborne microprocessor data collection system. Holder of second class FCC Radio Telephone License since 1969. 1975 - Colorado State University - supervisor of buildup, installation, and maintenance of electronic airborne meteorological data collection system.

Machinist. C. Wilkins. Air Force schools in electronics and precision equipment, 1954-1955; Supervisor of mill and tooling department at Heath Engineering Company, Ft. Collins, 1962-1967; Heavy Equipment operator, Ideal Cement Company, 1958-1962; Instructor, Field Machinist. Eastman Kodak, Windsor, Colorado, 1973; Certification in T.I.C., M.I.G., Arc and gas welding, Eastman Kodak, Windsor, Colorado, 1974. Experienced in fabricating and maintaining all mechanical devices used in conjunction with Severe Storm Research such as modification of FPS-18 radar, design and fabrication of mechanical phases of aircraft instrumentation including instrument booms on F-101B and T-28 aircraft. Installed doppler radar and antennas on Beechcraft Queen Air and T-28 aircraft. Perform as active flying crew member operating instrument package on Beechcraft



Queen Air and T-28 aircraft. Perform as ground crew member such as operating ground units, high pressure compressors, hydraulic units, and tow tractors; also, including pre-flight and post-flight inspections on F-101B, Queen Air and T-28 aircraft, 1970-1972 and present.

Aircraft Maintenance Chief: J. Wilkey. Performs routine and non-routine maintenance and inspections on F-101B aircraft and AADS-3B system used in support of airborne atmospheric storm research, 1971 - present. Holds current FAA airframe and powerplanned mechanic license #1904297. Trans World Airlines, Los Angeles, California, A & P mechanic performed maintenance on the following type aircraft: Boeing 727, 707, 747 and the Convair 880. (T.W.A. 747 systems school 40 hours) 1970-1971. Boeing Aircraft Company, Everett, Washington, Pre-flight and delivery mechanic on the 747. Boeing schools 747 main entry door's familiarization and rigging, 747 wet fuel cell entry and 747 structural familiarization, 1969-1970. United States Air Force, crew chief on the following type aircraft: RF-101C, RF-4C and F-4D. ACFT maintenance technician course and AFCT mechanic jet engine course, 1964-1968. Spartan school of aeronautics, Tulsa, Oklahoma, 1968.

Graduate Research Assistant:

1. Capt. James Stobie: Masters Degree Candidate, completed M.S. Jan. 1976. Subject: Gravity wave initiation by overshooting dome structure of severe storms,
2. Allan Schanot: Masters Degree Candidate, will complete M.S. Dec. 1976. Subject: Cloud modelling research.
3. Peter Wetzel: Ph.D. Degree Candidate, will complete Ph.D. July 1976. Subject: Sub-cloud boundary layer research.

IX. Appendix

PROGRESS REPORT

PERIOD: 7 FEB. - 30 SEPT. 1975

Department of Atmospheric Science

Colorado State University  
Fort Collins, Colorado  
80523

November 21, 1975

NASA Scientific and Technical  
Information Facility  
Post Office Box 8757  
Baltimore and Washington International  
Airport, Maryland 21240

Subject: NASA Research Grant NSG 1023 - Aircraft Measurement and  
Analysis of Severe Storms

Dear Sir:

I have outlined below a summary of the aircraft field program conducted by Colorado State University (CSU), Severe Storm Measurement and Analysis Group (SSMAG) under NASA Contract NSG #1023 for the period ending September 30, 1975. The purpose of this program was developed from the long standing need for a better understanding of severe convective storms which are at times a critical threat to our lives and to the social-economic standards of the country. As in many areas of the Atmospheric Sciences we are severely deficient in the development of a proper description of the severe storm system(s) due to the lack of accurate and representative measurements. To satisfy this requirement, SSMAG has developed, and tested with NASA support, a highly mobile, severe storm research aircraft capability. The major results and significance of these results for the initial phases of this program are outlined below:

#### Major Results

A. Initially, the most significant step of the aircraft measurement program was the acquisition of the aircraft and the design, fabrication installation, and testing of the instrumentation systems within the short time frame afforded by the contract start date of 7 February 1975. By 25 February 1975 we had purchased two aircraft (Figures 1 and 2), employed the necessary technicians, engineers, pilots, and etc., and were well into the design and fabrication stages of the airborne instrumentation. On 15 April these two aircraft had been completely modified, instrumented, and tested for the ensuing severe storm season. In addition, SSMAG had prepared and calibrated a third aircraft (F-101B severe storm penetration aircraft) which we have used previously to investigate the turbulent structure of the storm interior (Figure 3). Along with the instrumentation requirements of the primary NASA program, SSMAG also installed a NASA piggyback experiment designed to monitor the radio emission spectrum from severe storms. This involved the installation of a 450 lb. system in the Queen Air aircraft along with numerous (5) antennas mounted at widely spaced locations on the aircraft fuselage. In addition to the NASA support,

CSU provided three aircraft (approx. value \$500,000) and two airborne atmospheric data systems (value \$210,000). The development of this airborne research capability (3 aircraft, instrumentation systems, personnel, operating base, logistics, etc.) within the 68 days between 7 Feb. - 15 April 1975 was a major accomplishment. As a result, SSMAG can now deploy three fully instrumented, atmospheric research aircraft for the express purpose of obtaining severe storm data in three cloud regions: (1) sub-cloud, (2) mid-level environment, and (3) in-cloud environment by direct penetrations. These data will provide the necessary initial and boundary conditions from which future severe storm descriptive and analytical-numerical models will be developed.

B. In order to maximize both the number and type of severe storm cases desired, we have designed our aircraft field measurement program to be as flexible as possible in order to meet the NASA mobility requirements. These mobility requirements are largely due to the wisdom and foresight of Dr. Shenk of NASA, Goddard. The mobile aircraft deployment plan is a new concept in severe storm research in that it requires deployment of the research aircraft, logistics, and communication systems to the forecast severe storm area within a 48 hr. period. During the spring storm season we field tested this technique with all three aircraft (3 additional NASA aircraft were also involved). In most cases, we were successful in placing all three research aircraft in the severe storm area prior to storm development. In some cases we deployed successfully with only a 24-36 hr. notice. It is important to note, that in the past, severe storm research projects have been of a fixed network type. That is, the deployment of this type of airborne system(s) has not been concerned with development of communication systems, logistics, and FAA traffic control procedures outside of a relatively small geographical area. From our field experience last spring, we are now capable of deploying all three aircraft with the necessary logistics support to any severe storm forecast area in the midwest within a 48 hour period. We believe this is the first time that atmospheric research aircraft, ground crews, and support equipment have been specifically developed into a highly mobile facility for monitoring moving severe storm systems. This aircraft measurement capability is in some ways analogous to the highly successful NOAA hurricane aircraft monitoring system. We expect this mobile capability during the 1976 spring storm season to provide us with many more severe storm cases of the proper type and intensity than that offered by a fixed base field program.

C. Although last year was primarily an aircraft instrument development, testing, and deployment phase, we were successful in obtaining environmental data near and around several severe storms. In addition, simultaneous measurements were obtained on the severe storm radio emission spectrum. These data are still in the processing and analysis phase and therefore the measurement results are not available at this time. It is anticipated that these data will be useful in deducing storm movement and entrainment of environmental air--the latter is of crucial importance with respect to the storm's development and dissipation phases. The

November 21, 1975

Page 3

electrical measurements are designed to test the hypothesis that tornadic storms have discrete radio emission signatures that may prove useful in a satellite remote detection and alarm system.

D. In order to support and maintain the research aircraft and instrumentation systems, the CSU Atmospheric Science Department has established an Airborne Research Flight Facility (ARFF) at the Fort Collins-Loveland Airport. This facility provides, or has access to, the necessary hangars, maintenance shops, flight planning and maintenance operations offices, and program briefing sections. The airport has a 6700 foot runway which is sufficient for operating the T-28 and the Queen Air under various load and weather conditions. The F-101B is operated from Buckley ANG Base near Denver (approx. 60 miles south of Fort Collins). A satellite operation's base has been established there to provide the necessary maintenance and flight operations support.

The initial development and field tests of the CSU severe storms measurement and aircraft facilities (SSMAG and ARFF) has been essentially completed. We believe that their full potential will be realized during the 1976 severe storm season.

Sincerely,

Peter C. Sinclair  
Associate Professor

PCS:kr

Enclosures

## X. Figures and Tables

Figure 1: Upper Level Severe Storms Measurement Aircraft

The McDonnell F-101B jet interceptor has been extensively modified to carry the AADS-4A system. In order to preserve the excellent radar system (MG-13), the nose instrumentation boom was installed above the radar antenna in an area previously occupied by IR or refueling equipment. The boom and supporting structure have been designed with ultimate load factors in excess of the aircraft. The total length of the boom is approximately 16 ft, with 9 ft of the boom projecting ahead of the aircraft. At present, the gyro-reference system, transducers, and all associated electronics are housed in a temperature controlled chamber in the nose of the aircraft. This system is being updated with the installation of an inertial platform in the aircraft missile bay. The missile bay is located on the bottom of the aircraft directly below the cockpits. It's size (7.0' x 4.0' x 2.5') the temperature controlled environment make it an ideal instrumentation location.

The aircraft is equipped with UHF, VHF, and FM radio communications. Either TACAN, VOR-DME or VLF can be used for navigation. The aircraft is shown here with one 450 gal. drop-tank which, with internal fuel, provides approximately 2 hrs. on-station. Two drop-tanks can be carried, but storm penetrations are normally made "clean" or with one drop-tank due to superior flight characteristics.

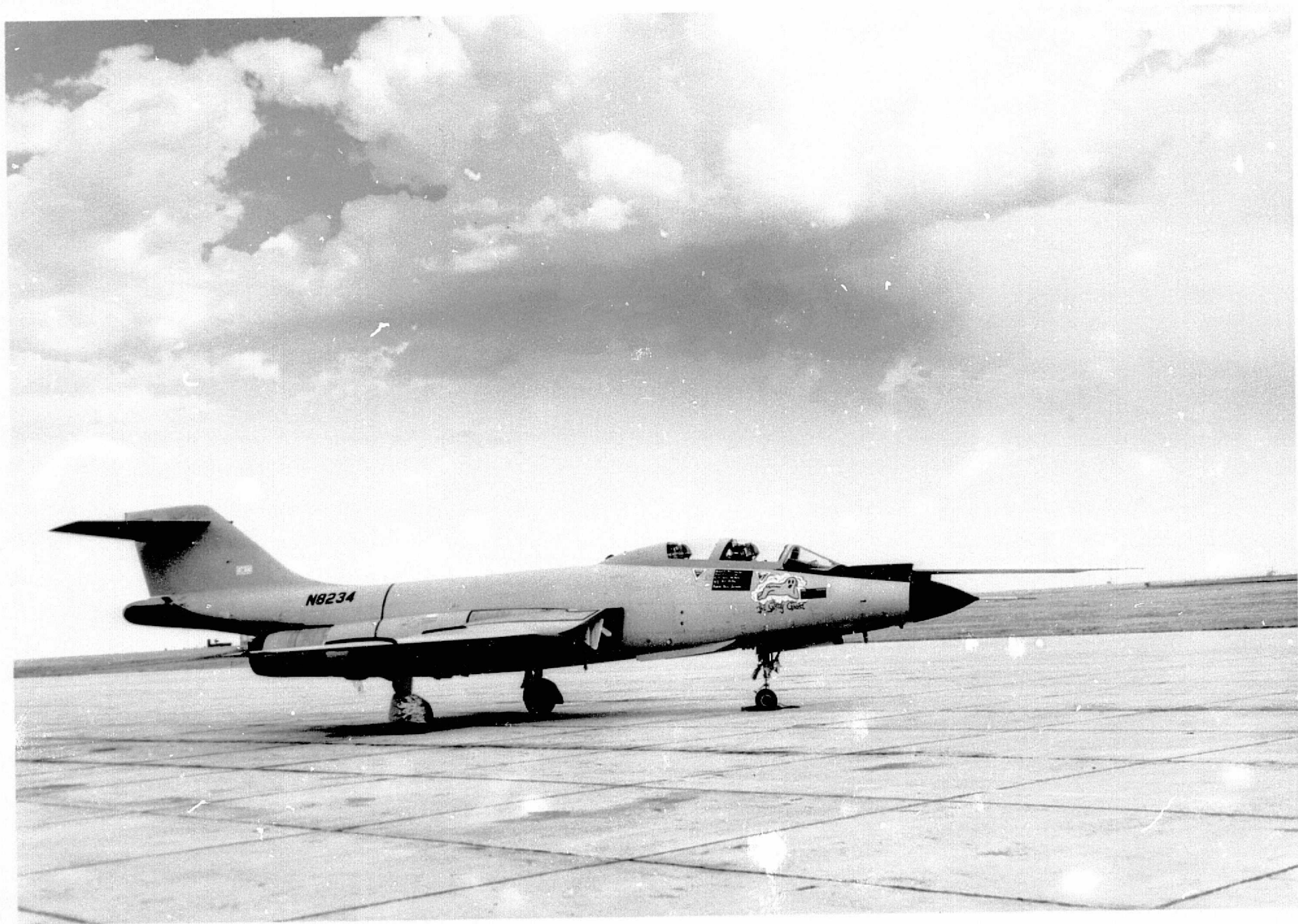




Figure 2: Mid Level Severe Storms Measurement Aircraft: Q.A. 1-80

The Q.A. A-80 research aircraft and AADS-5A is capable of measuring and recording the pressure, temperature, dew point and mid-cloud environmental wind. The horizontal mean winds are obtained from a doppler wind system (AN/APN153V) located in the rear of the aircraft. The antenna radome is shown (Fig. 2) aft of the wing on the bottom of the fuselage. A forward pointing radar in the nose is used to initially locate the storm for optimum cell intercept and to establish the optimum flight track(s) around the storm. Seven antennas have been added to the aircraft fuselage in order to monitor the storm lightning discharge spectra in the 3-300 MHZ frequency range. Approximately 400 lbs of receivers, power supplies, and recording systems are carried internally to support this NASA piggyback experiments.



Figure 3: Sub-Cloud Severe Storms Measurement Aircraft: N.A. T-28

The North American T-28 aircraft has been extensively modified to carry the AADS-2B system. The boom structure positions some of the sensing probes ahead of the aircraft propellor to minimize fuselage flow and pressure characteristics. The boom supports the Rosemount pitot-static tube and the  $\alpha$ - $\beta$  vane system. The  $\alpha$  and  $\beta$  vane units, along with the gyro referenced platform, provide data on the vertical and lateral air motions near and within the severe storms. The balsa vane are coated with a special abrasive coating and are internally mass balanced to improve the response characteristics. The boom is of aluminum-stainless steel construction and has a natural frequency of 11 cps. A doppler wind system (DN-153V) is located below the observer (bottom of the fuselage) for obtaining sub-cloud and shear-line wind measurements.

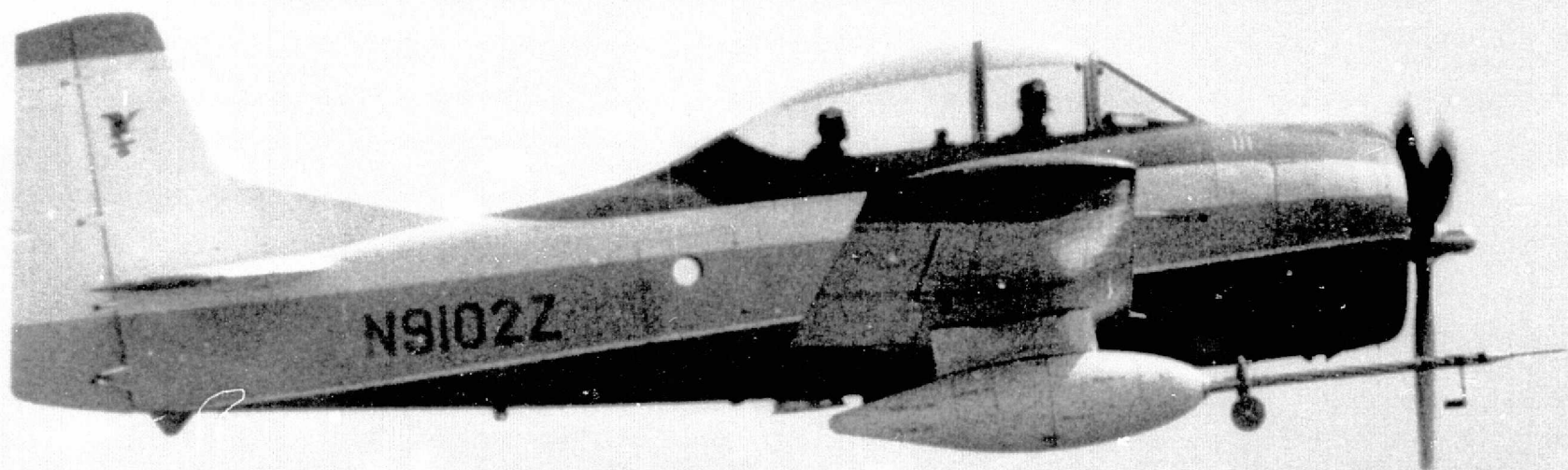


Figure 5: The AADS-4A Boom-Vane Pitot-Static System

The boom structure positions some of the sensing probes well ahead of the aircraft to minimize fuselage induced pressure and flow effects. The boom supports the Rosemount pitot-static tube and the  $\alpha$ - $\beta$  vane system. The  $\alpha$  and  $\beta$  vane units, along with the gyro referenced platform, provide data on the vertical and horizontal air motions near and within the severe storms. The balsa vanes are coated with a special abrasive coating and are internally mass balanced to improve the response characteristics. The boom is of aluminum-stainless steel construction and has a natural frequency of 12 cps. In over one hundred severe storm penetrations neither the boom system nor the specially constructed balsa vanes have suffered significant damage. The small pitot-static boom attached to the front of the radome is connected to the F-101B aircraft air data system.

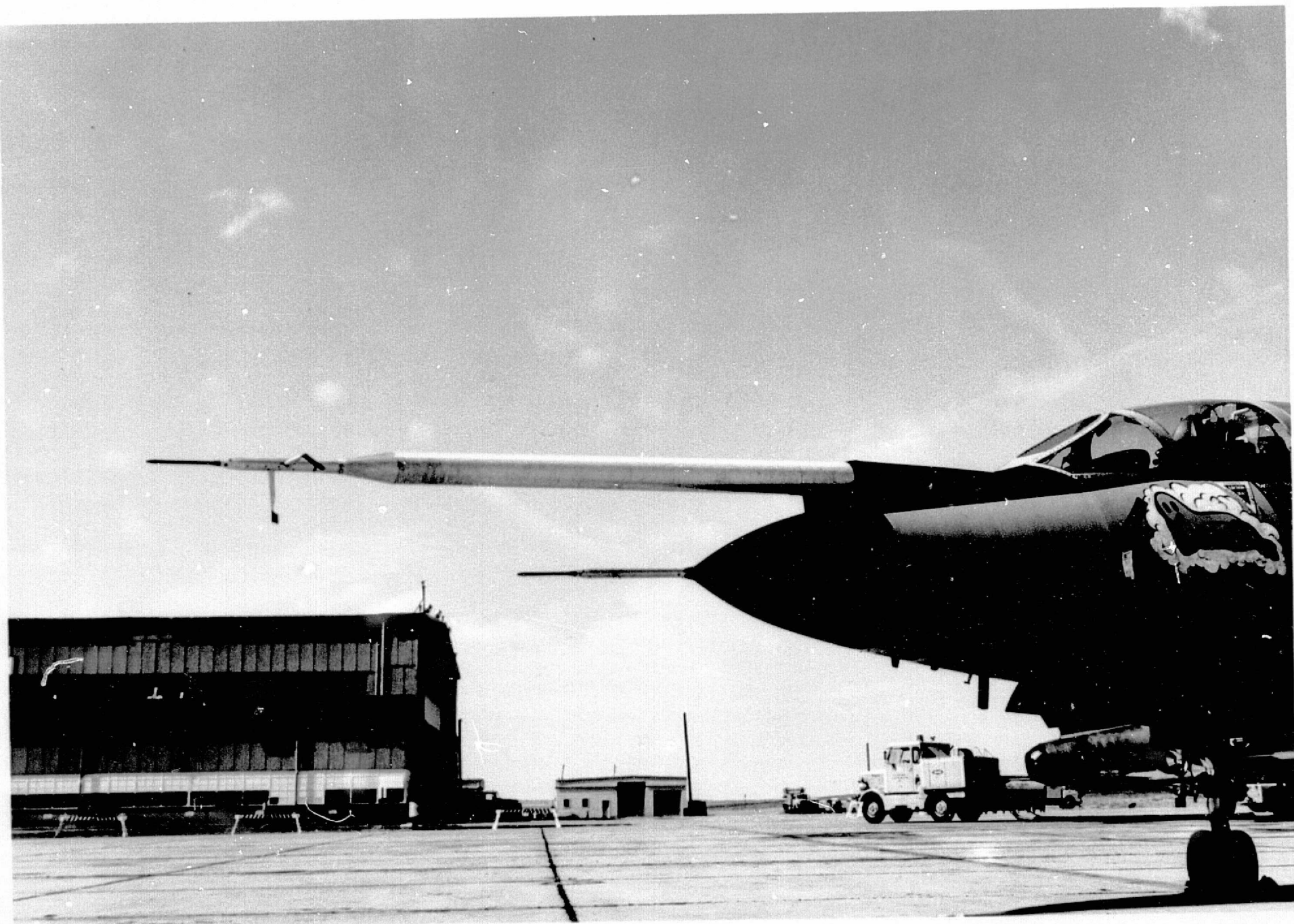
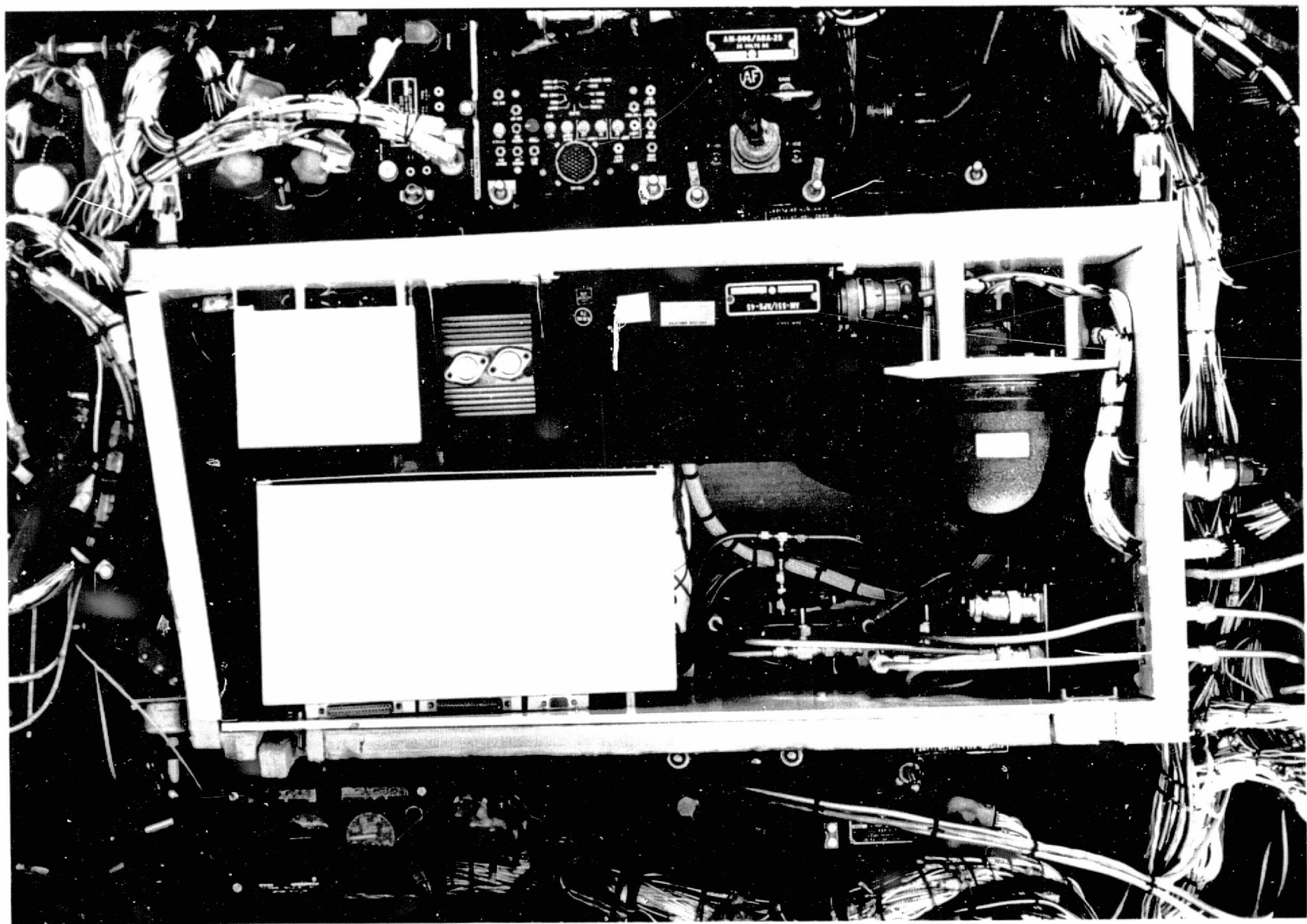


Figure 6a, b The AADS-4A Gyro Reference Platform and Signal Conditioning System

This unit is mounted in the nose of the F-101B and provides gyro referenced information on the aircraft orientation and movement as well as acting as a filtering and signal conditioning center for the twenty channels of data. The insulated unit is sealed (3b) and heated during flight in order to maintain all electronic and mechanical components at the laboratory calibration temperature of  $70^{\circ} \pm 4^{\circ}\text{F}$ . Space for the AADS-4A system was provided by removal of much of the fire control and data-link system which is of no use in the present research missions. The MC-13 radar system has been retained and is being modified to provide reflectivity and doppler wind information. The heated Rosemount total temperature sensor is shown at the bottom of the picture (3b) directly below the exposed nose instrumentation compartment. A second Rosemount temperature sensor to the left of the AADS-4A sensor is part of the F-101B air data system.







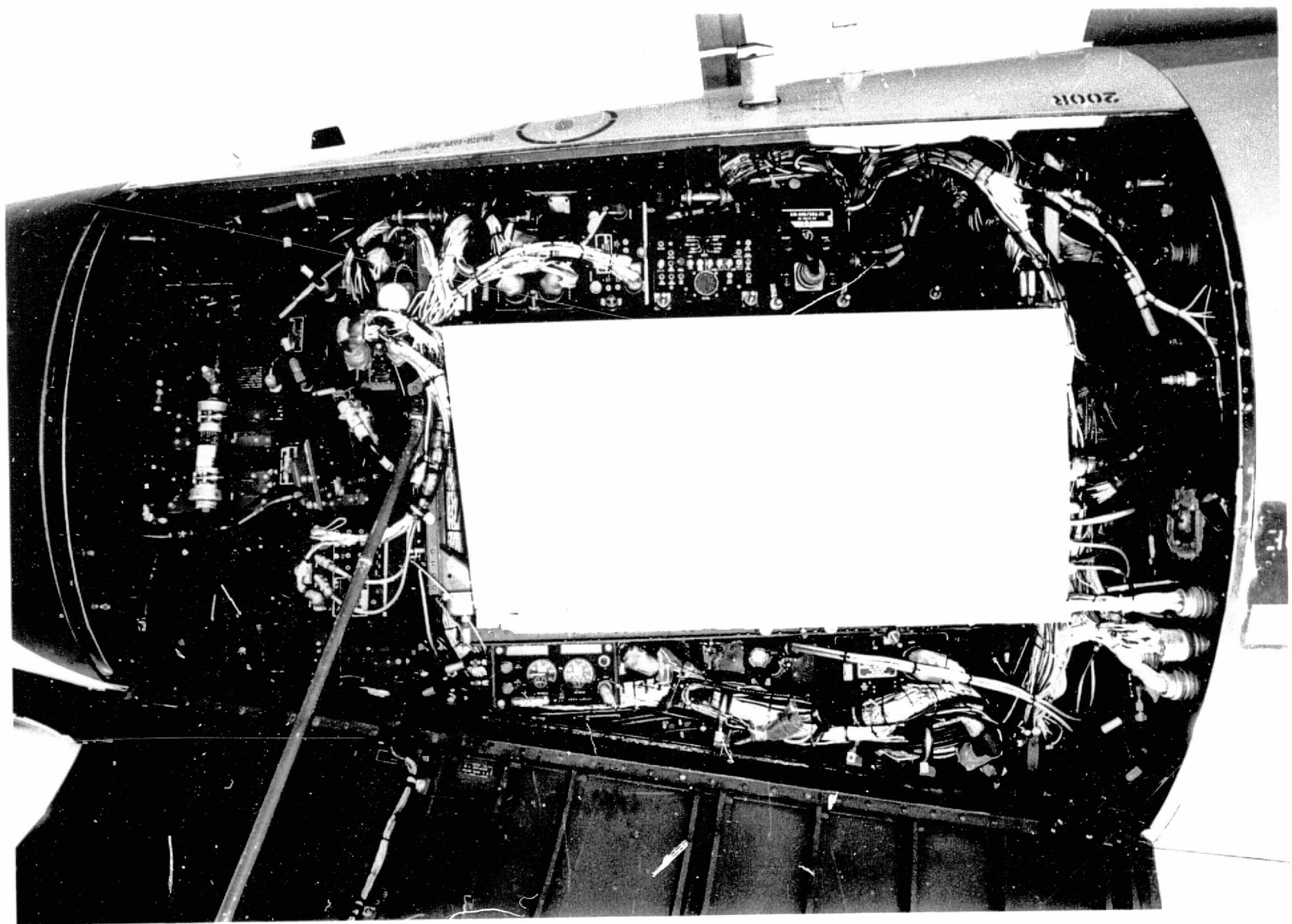


Figure 7: Recording and Control Center for AADS-4A System

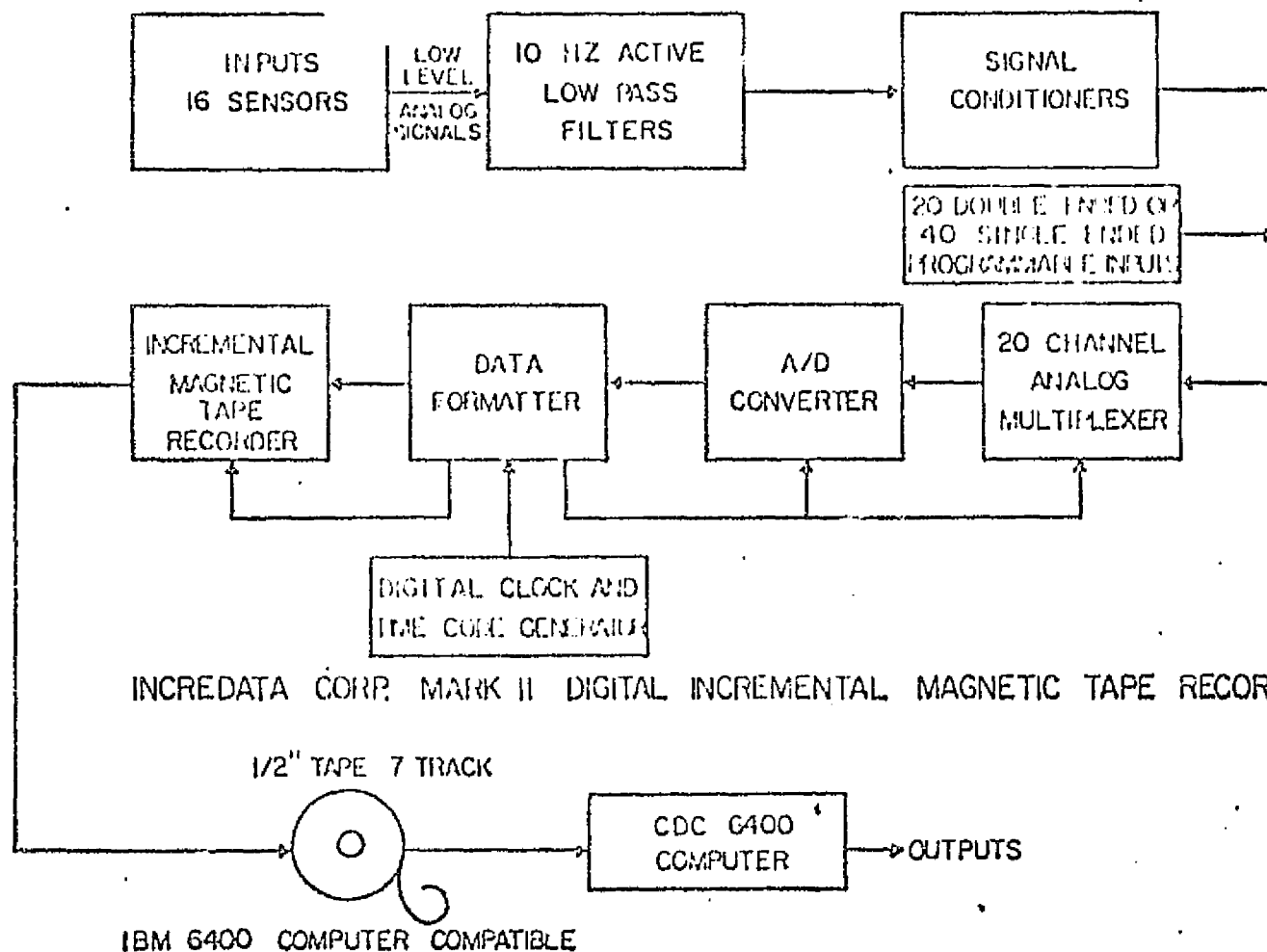
The AADS-4A recording and control center is located in the rear cockpit of the F-101B and is operated and monitored by the second crew member. All twenty channels of data are recorded on the Mark II incremental, digital tape recorder (lower center). The oscilloscope shown below the flight instrument panel is used to monitor all recorded channels before and after each cloud penetration. The MG-13 radar system allows both manual and automatic scan of the cloud reflectivity regions which are displayed on a 7 inch radar screen in front of the radar operation (screen not shown in picture). A Hasselblad camera is used to photograph the storm before and after the penetrations.



Figure 8: Schematic of AADS/4A Measurement System

To eliminate aliasing errors, the sensor signals pass through an 8-pole Butterworth filtering system and are then conditioned for a bipolar 0-2 volt input level. The signals are then sampled at 50 per second in the Incredata Mark II digital, incremental magnetic tape recording system. The Mark II is a complete data acquisition system in that it includes in one package: (1) a multiplexer, (2) an A/D converter, (3) a time code generator, (4) a data formatter, and (5) a cartridge-loaded incremental magnetic tape recorder. The tape output is fully IBM compatible with standard IRIG and EOR gaps.

# F-101B AADS-4A AIRBORNE SYSTEM



INCREDATA CORP. MARK II DIGITAL INCREMENTAL MAGNETIC TAPE RECORDING SYSTEM

1/2" TAPE 7 TRACK

CDC 6400  
COMPUTER

OUTPUTS

IBM 6400 COMPUTER COMPATIBLE

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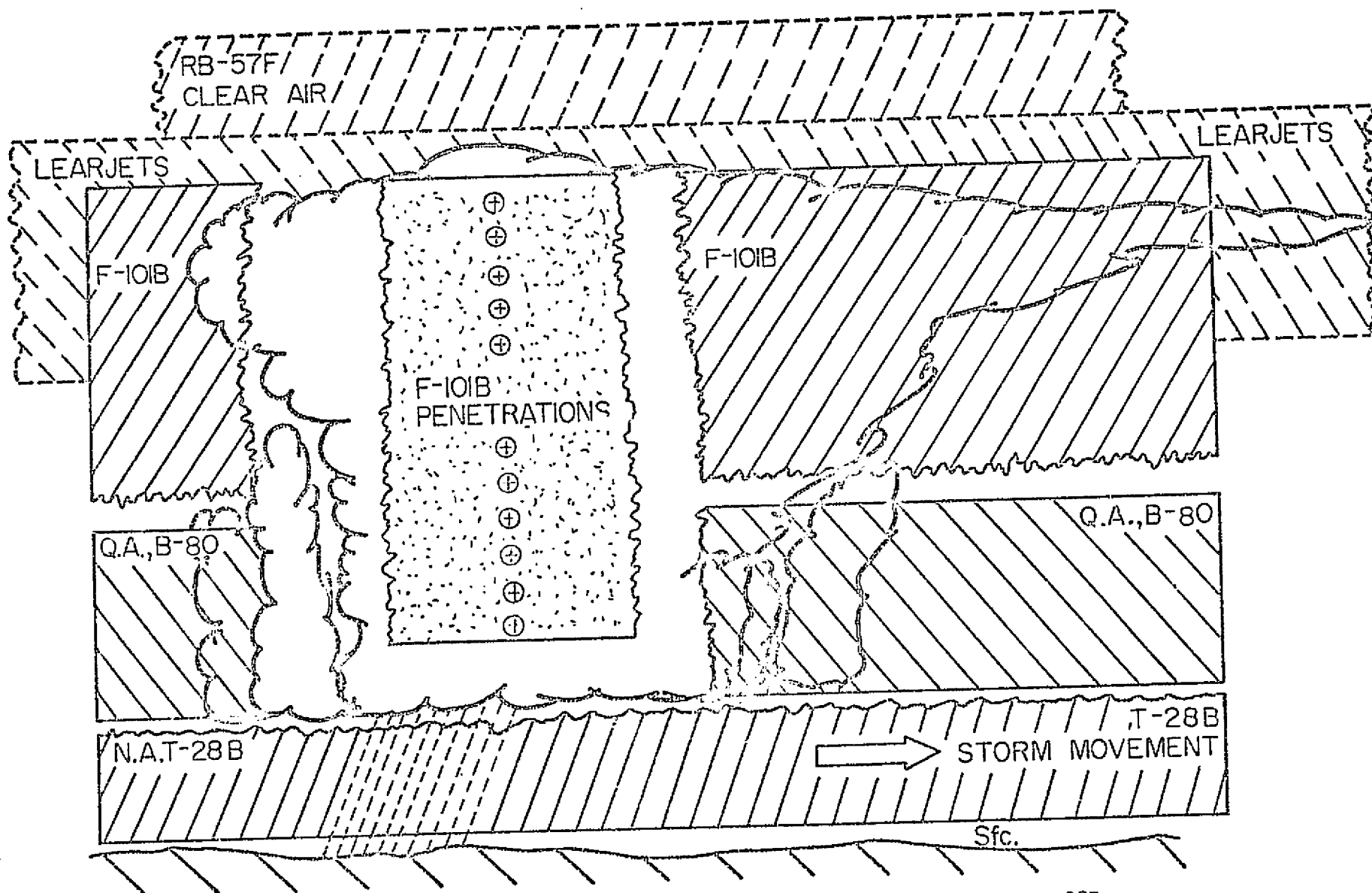


Figure 9: Research Aircraft Flight Altitude Blocks. The F-101B, Q.A.B-80, and T-28B are CSU research aircraft (solid boundaries). The dashed boundaries represent severe storm research aircraft supplied by other agencies.

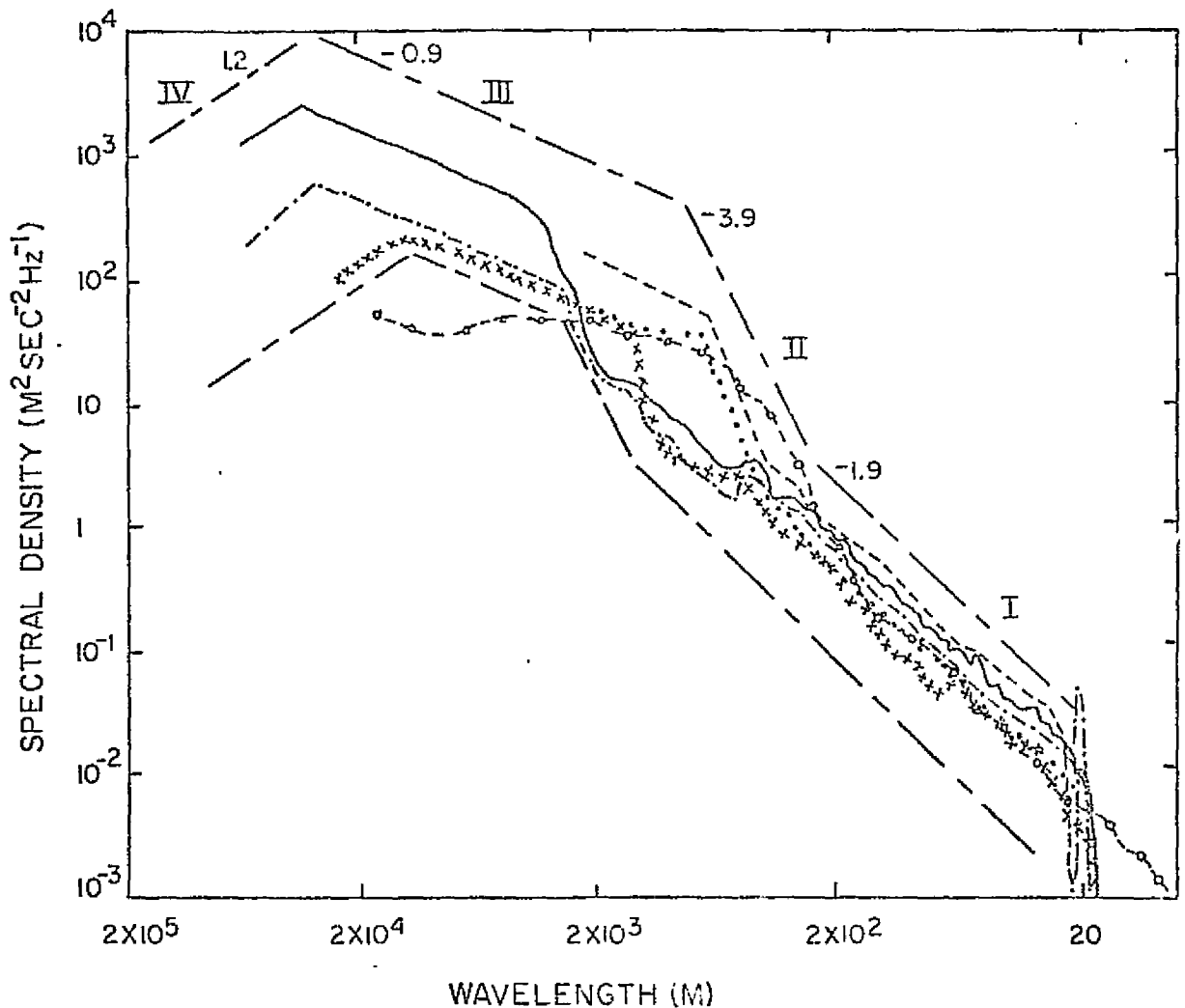


Fig. 10: Spectra of vertical velocity component ( $w$ ) obtained from aircraft measurements near and within severe storms. Region II represents a transition region between the energy input range (III and IV) and a quasi-inertial sub-range (I). The mean slopes of the spectral curves for each region are shown by the bounding dashed lines. The high frequency oscillation at  $\lambda \sim 20$  m represents the upper limit of the electronic and digital filtering frequency for high speed aircraft. Low-speed aircraft spectral density curves extend down to  $\lambda \sim 6$  m for the same filter cutoff frequency of 10 Hz because of the lower true airspeeds.

# AIRCRAFT MEASUREMENTS OF SEVERE STORMS: 1975

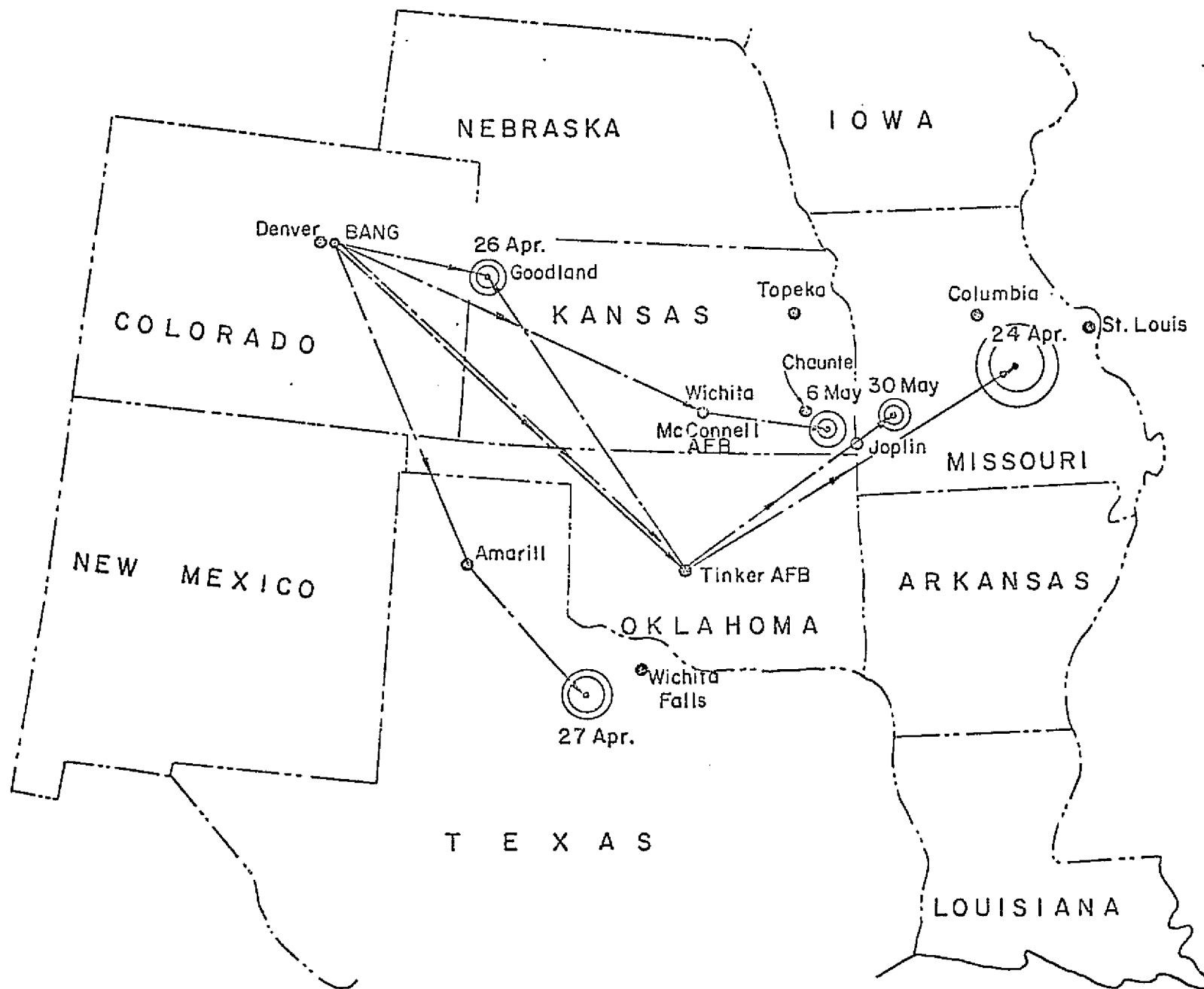


Figure 11: Location of Aircraft Measurements of Severe Storms: 1975



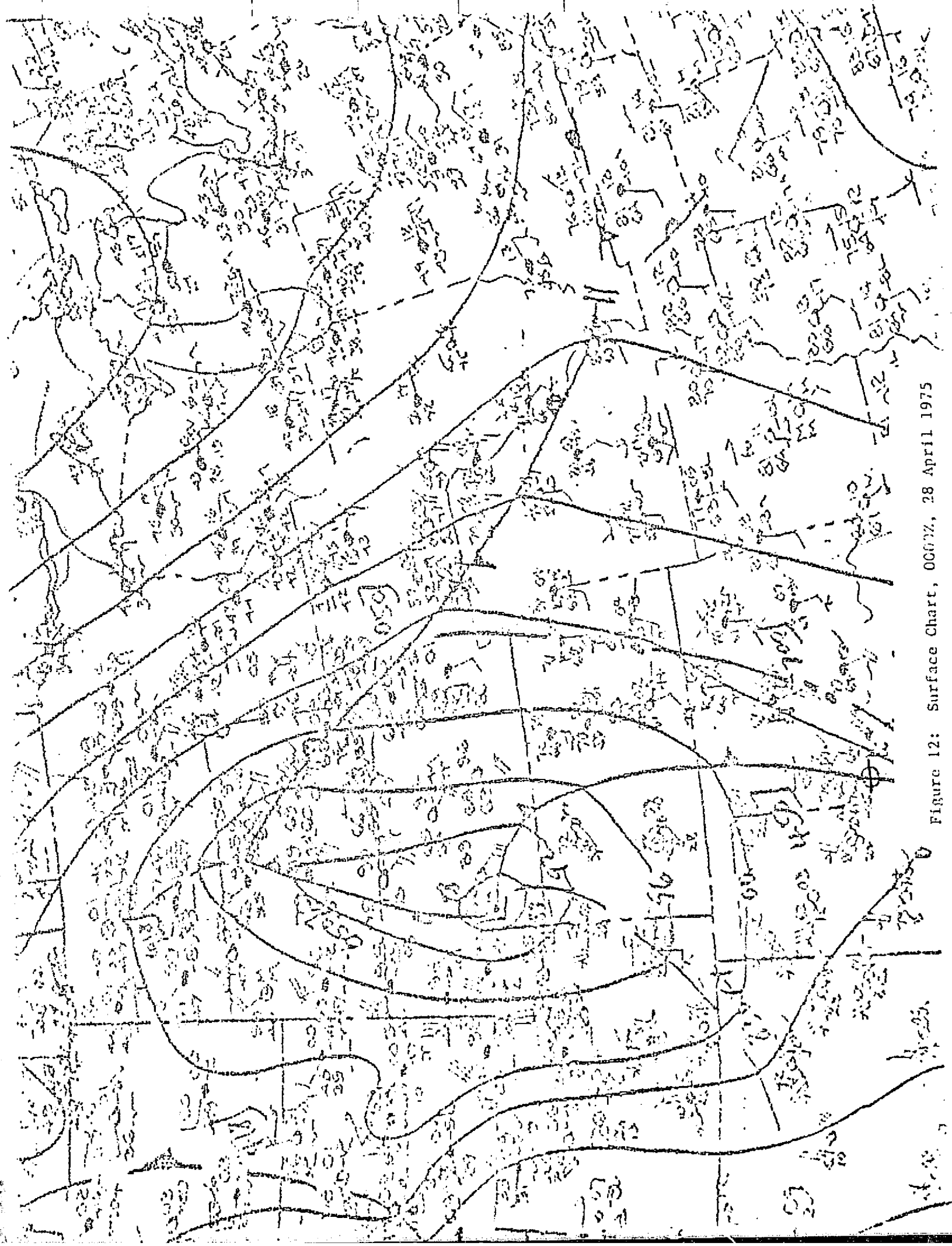


Figure 12: Surface Chart, 000%, 28 April 1975

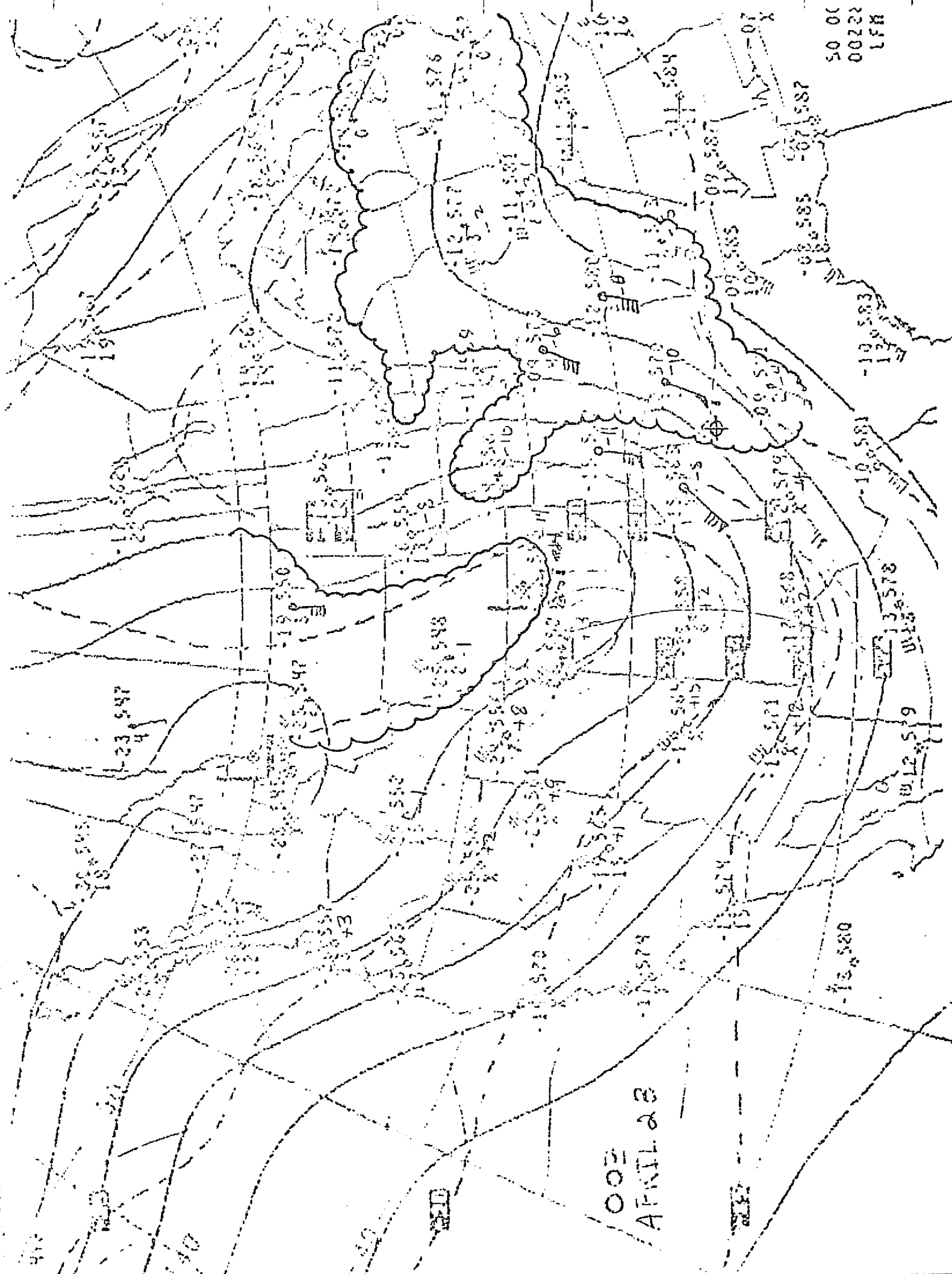


Figure 13: 500 mb Chart, 0000Z, 28 April 1975

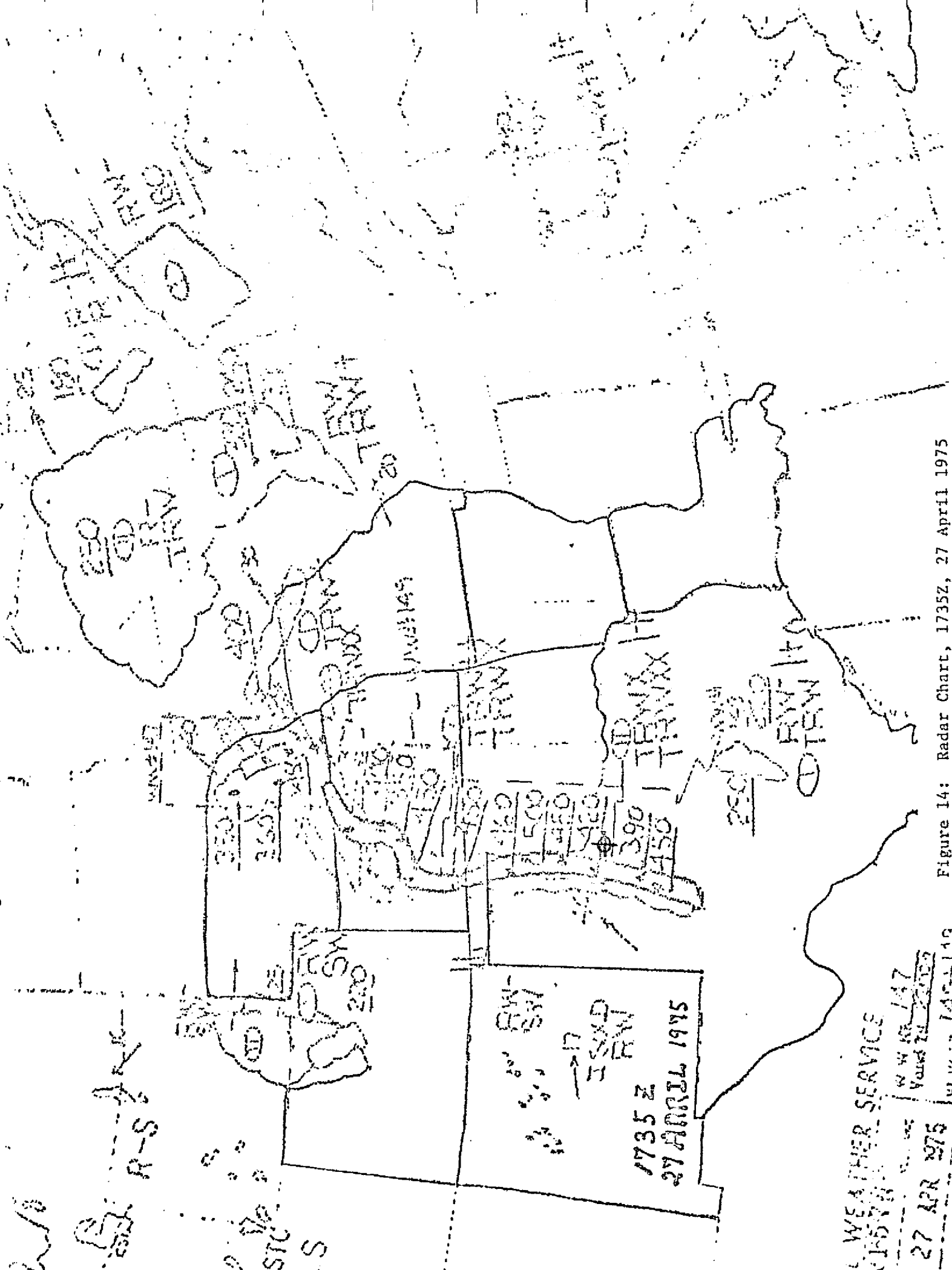
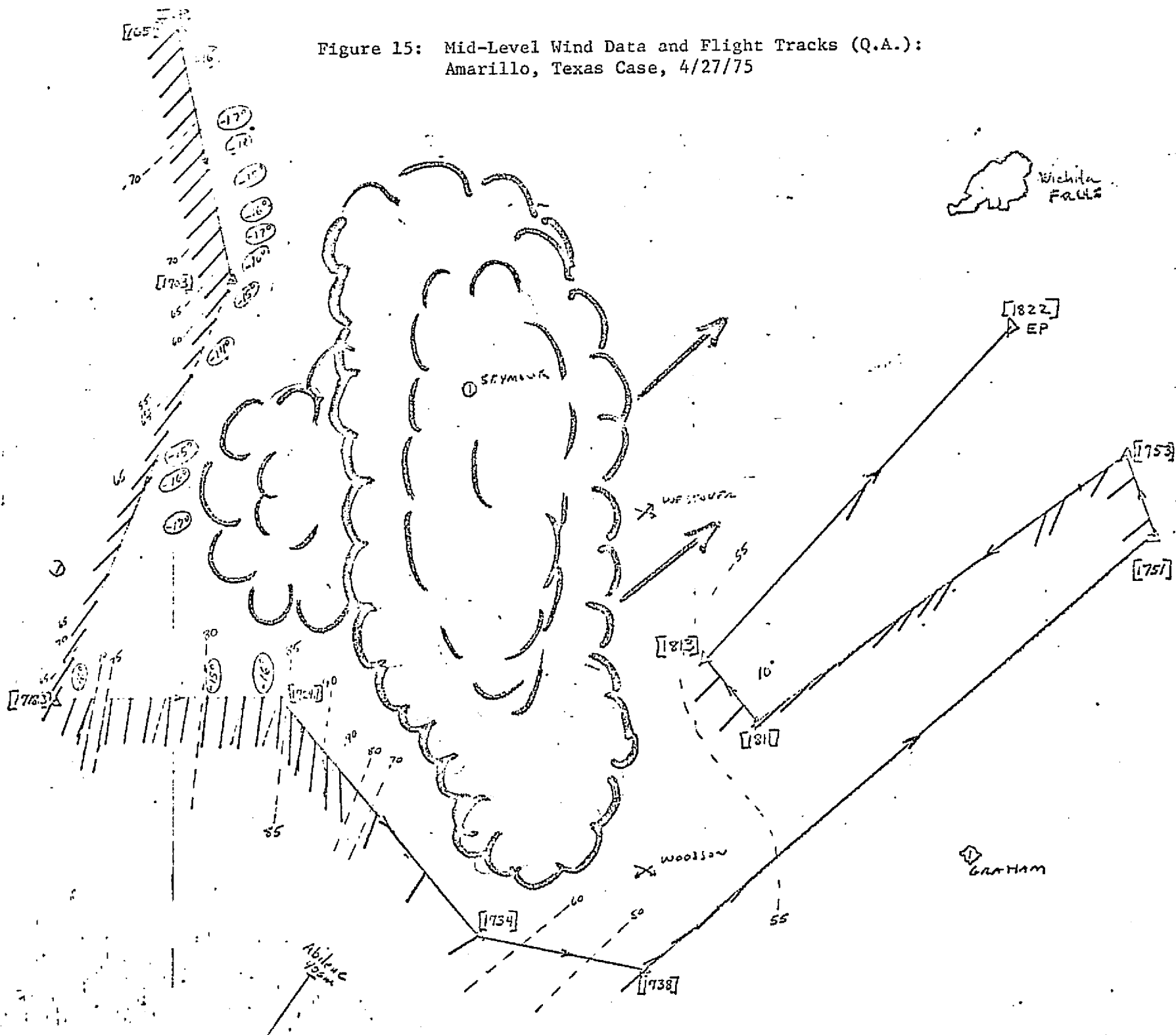


Figure 14: Radar Chart, 1735Z, 27 April 1975

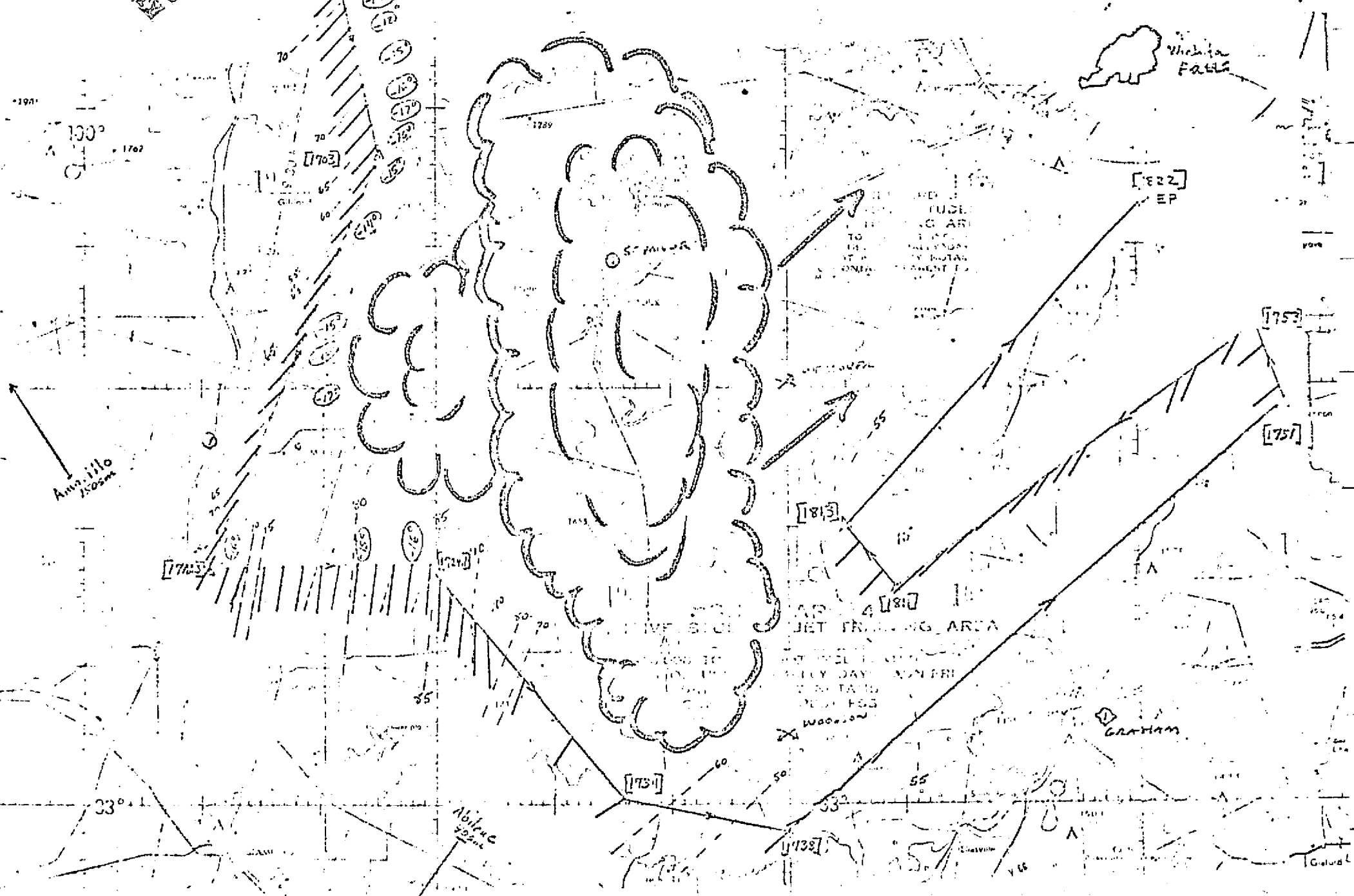
U.S. WEATHER SERVICE  
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Figure 16: Mid-Level Wind Data and Flight Tracks-Sectional Base (Q.A.):  
Amarillo, Texas Case, 4/27/75



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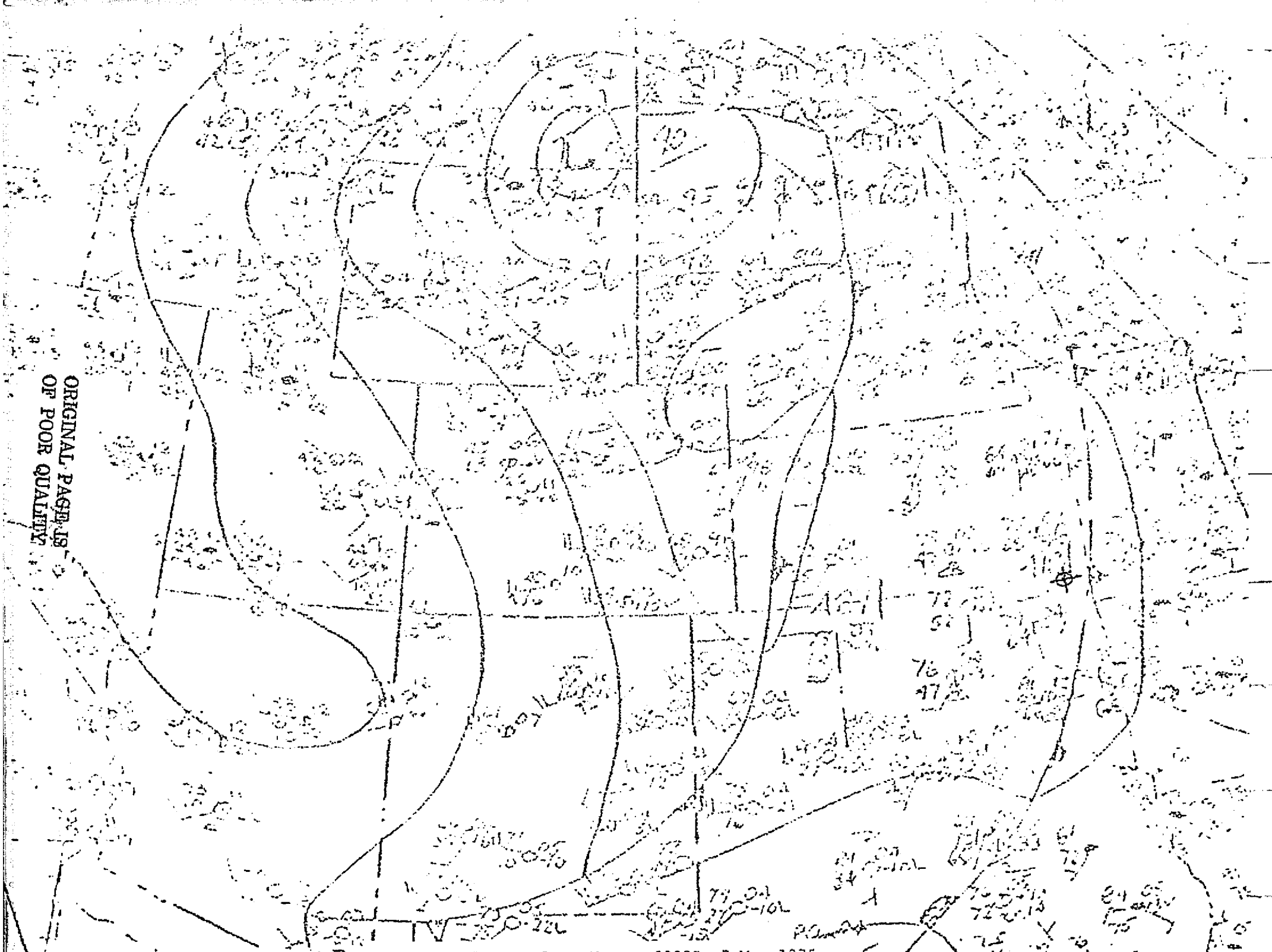


Figure 17: Surface Chart, 00002, 7 May 1975

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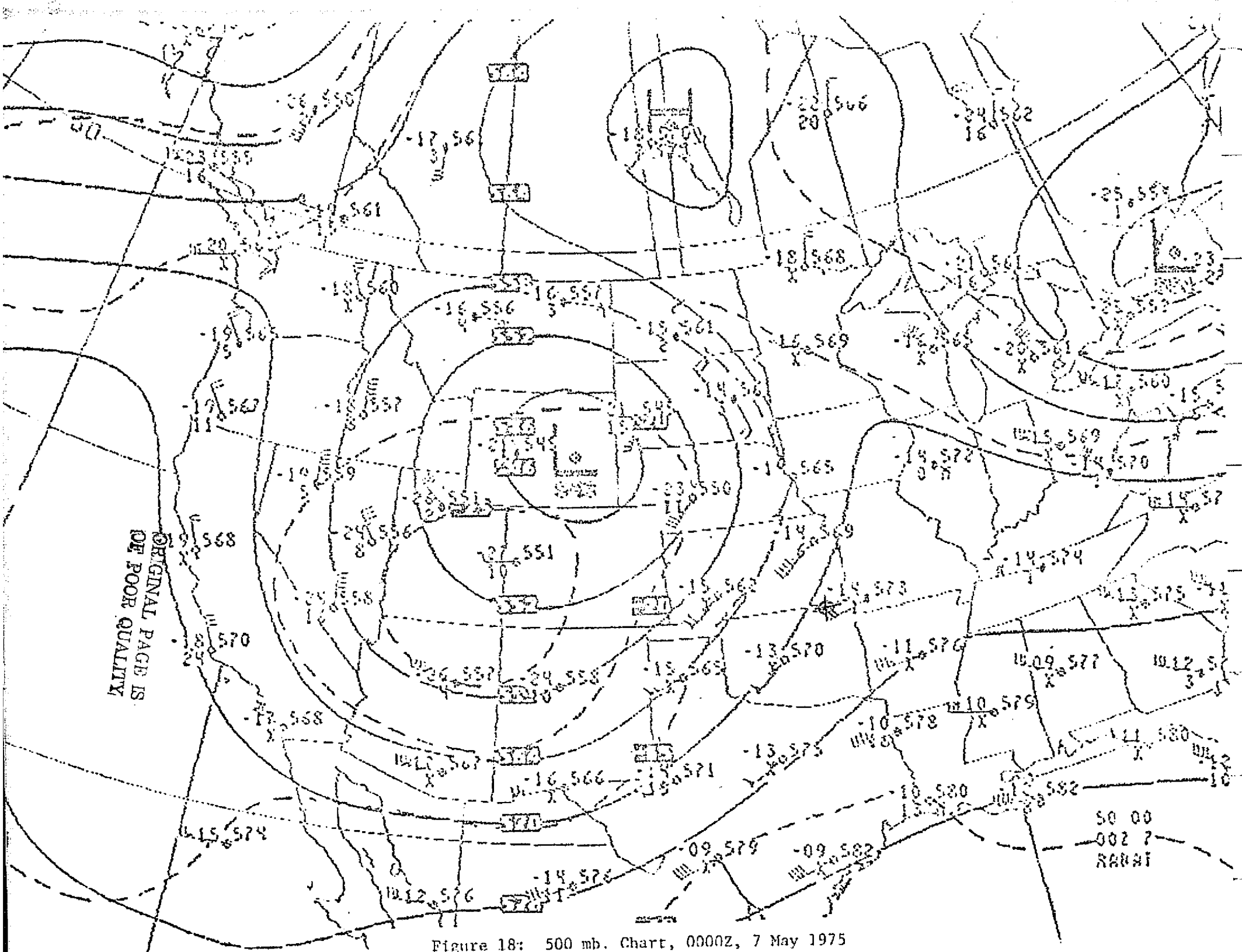


Figure 18: 500 mb. Chart, 0000Z, 7 May 1975





Figure 20: Mid-Level Wind Data and  
Flight Tracks (Q.A.): SE  
Kansas Case, 5/6/75

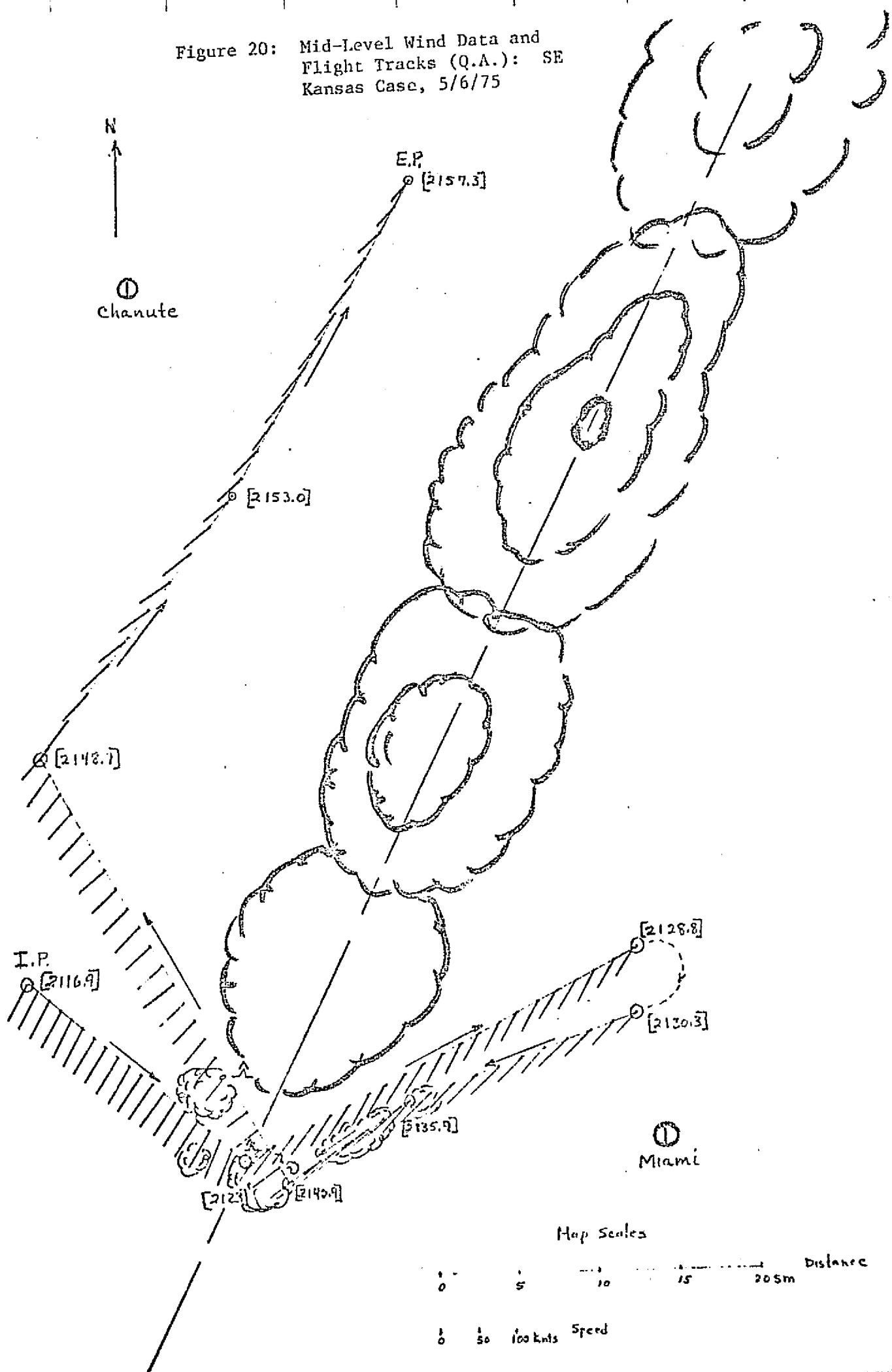
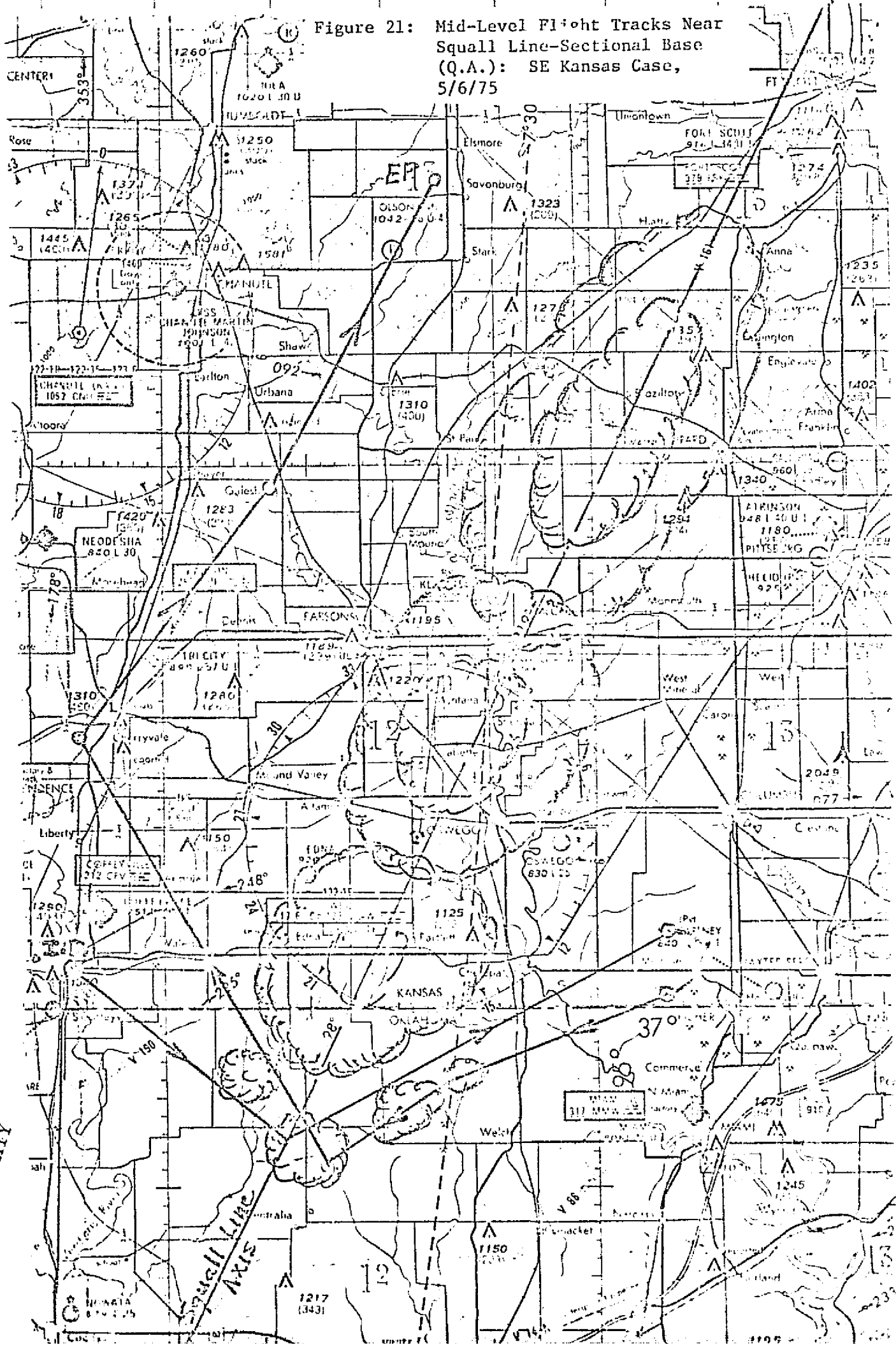


Figure 21: Mid-Level Flight Tracks Near  
Squall Line-Sectional Base  
(Q.A.): SE Kansas Case,  
5/6/75



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DATE - 27 APRIL 1975  
ACFT - QUEEN AIR, #1210  
LOCATION - AMARILLO STORM

T.R.	TIME	R.T.	U (KNOTS)	V (KNOTS)	VH (KNOTS)	WIND (DEG)	DEW POINT (C)	TEMP (K)	ALTITUDE (M)
54 9	1654.0		-51.7	39.7	65.2	224.4	-15.9	271.5	4544.4
5414	1654.1		-56.3	40.1	64.1	224.7	-15.1	271.3	4572.1
5419	1654.2		-59.7	40.7	72.3	224.6	-15.1	271.1	4572.3
5424	1654.2		-60.5	34.4	71.7	224.0	-15.1	270.9	4570.4
5429	1654.3		-61.1	37.4	71.6	223.0	-15.0	270.9	4573.4
5434	1654.4		-62.0	35.0	71.7	221.3	-15.0	271.1	4572.9
5439	1654.5		-56.8	37.4	68.4	224.2	-15.9	271.2	4572.8
5444	1654.6		-54.2	37.4	64.2	224.1	-15.8	271.4	4573.7
5449	1654.7		-52.1	39.7	55.5	227.3	-15.4	271.5	4571.7
5454	1654.7		-51.9	38.6	54.5	226.7	-15.2	271.5	4567.6
5459	1654.8		-53.1	38.1	65.4	224.0	-15.9	271.4	4566.0
55 4	1654.9		-55.8	35.5	65.7	224.1	-15.8	271.3	4572.8
55 9	1655.0		-54.9	35.0	64.0	222.6	-15.7	271.2	4577.3
5514	1655.0		-54.3	36.8	69.0	224.4	-15.7	271.1	4575.4
5519	1655.1		-57.4	37.8	64.7	224.5	-15.7	271.1	4577.1
5524	1655.2		-56.6	39.8	68.2	225.3	-15.8	271.2	4577.4
5529	1655.3		-54.1	40.0	67.3	227.1	-15.8	271.3	4578.6
5534	1655.4		-52.0	37.2	64.7	225.4	-15.7	271.3	4577.5
5539	1655.4		-53.4	37.3	65.1	225.7	-15.7	271.3	4577.1
5544	1655.5		-55.1	34.2	67.6	226.1	-15.9	271.3	4577.2
5549	1655.5		-55.0	34.8	67.4	224.3	-15.1	271.2	4577.6
5554	1655.7		-55.8	36.1	64.2	225.3	-15.3	271.2	4575.0
5559	1655.7		-55.4	38.1	67.2	225.4	-15.4	271.2	4576.0
56 4	1655.8		-52.5	37.8	64.8	226.5	-15.4	271.2	4576.5
56 9	1655.9		-53.8	38.3	65.0	227.6	-15.2	271.3	4573.5
5614	1656.0		-55.7	36.1	65.9	225.7	-15.2	271.2	4573.7
5619	1656.1		-56.7	36.5	67.4	225.1	-15.2	271.1	4575.4
5624	1656.2		-57.3	35.0	67.6	224.4	-15.3	271.1	4573.7
5629	1656.2		-53.3	37.5	64.5	226.6	-15.6	271.1	4574.2
5634	1656.3		-55.7	35.8	67.1	223.4	-17.0	271.0	4574.4
5639	1656.4		-56.8	37.3	64.7	223.5	-17.5	271.0	4574.5
5644	1656.5		-56.0	37.1	67.2	224.7	-17.3	271.1	4574.7
5649	1656.5		-53.5	38.1	65.7	224.9	-17.2	271.3	4572.0
5654	1656.6		-55.3	37.8	65.9	224.3	-17.2	271.3	4573.5
5659	1656.7		-53.8	37.1	65.3	224.3	-17.3	271.2	4573.5
57 4	1656.8		-54.1	37.1	64.8	226.5	-17.5	271.3	4573.7
57 9	1656.9		-52.5	35.5	64.0	226.3	-17.7	271.3	4570.0
5714	1657.0		-52.4	35.2	63.1	225.2	-17.8	271.5	4566.4
5719	1657.0		-50.0	33.9	60.4	225.5	-17.5	271.6	4560.0
5724	1657.1		-50.1	35.0	61.2	224.3	-17.5	271.4	4572.8
5729	1657.2		-54.1	35.0	64.9	225.4	-17.3	271.6	4574.5
5734	1657.3		-56.4	35.5	66.7	224.7	-17.3	271.2	4574.3
5739	1657.4		-55.5	35.0	67.0	225.0	-17.6	271.1	4574.3
5743	1657.4		-55.4	35.1	69.0	223.1	-17.5	271.0	4573.7
5748	1657.5		-57.4	35.5	67.5	224.0	-17.6	270.9	4573.2
5753	1657.6		-58.0	33.2	65.8	222.6	-17.8	270.6	4570.8
5759	1657.7		-62.3	37.1	72.5	223.7	-17.8	270.7	4574.3
58 3	1657.8		-64.3	34.5	72.7	221.0	-17.7	270.6	4574.1
58 8	1657.8		-64.8	34.5	73.5	221.4	-17.6	270.5	4574.7
5813	1657.9		-65.2	34.2	73.6	221.3	-17.5	270.5	4574.7
5818	1658.0		-66.1	36.0	75.3	222.2	-17.5	270.5	4575.1
5823	1658.1		-64.1	36.0	73.5	222.8	-17.6	270.6	4575.1
5828	1658.2		-63.5	35.2	73.1	222.4	-18.0	270.6	4575.0
5833	1658.3		-60.1	38.1	73.7	224.0	-20.2	270.6	4574.2
5838	1658.3		-63.7	35.0	73.5	222.8	-21.0	270.5	4574.4
5843	1658.4		-64.7	38.7	72.5	222.2	-20.2	270.5	4574.4

Table 1: Wind, Temperature, and Dew Point Tabulations:  
27 April 1975, Amarillo, Texas Case

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DATE - 27 APRIL 1975  
ACFT - QUEEN AIR 612JO  
LOCATION - AMARILLO STORM

DATE - 27 APRIL 1975  
ACFT - QUEEN AIR 612JO

LOCATION - AMARILLO STORM

T.P.	TIME	U.T.	U (METS)	V (METS)	VM (METS)	TEMP (C)	DWP POINT (C)	TEMP (K)	ALTITUDE (M)
2013		1470.1	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2014		1470.2	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2015		1470.3	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2016		1470.4	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2017		1470.5	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2018		1470.6	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2019		1470.7	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2020		1470.8	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2021		1470.9	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2022		1471.0	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2023		1471.1	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2024		1471.2	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2025		1471.3	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2026		1471.4	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2027		1471.5	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2028		1471.6	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2029		1471.7	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2030		1471.8	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2031		1471.9	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2032		1472.0	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2033		1472.1	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2034		1472.2	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2035		1472.3	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2036		1472.4	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2037		1472.5	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2038		1472.6	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2039		1472.7	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2040		1472.8	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2041		1472.9	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2042		1473.0	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2043		1473.1	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2044		1473.2	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2045		1473.3	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2046		1473.4	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2047		1473.5	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2048		1473.6	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2049		1473.7	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2050		1473.8	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2051		1473.9	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2052		1474.0	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2053		1474.1	-15.5	44.6	45.2	100.4	-15.3	271.3	4449.7
2054		1474.2	-15.5	44.6	45				



DATE - 27 APRIL 1975  
ACFT - GUNFIRE ATP. #1210  
LOCATION - ANAVALLO STONY

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Table 2: Wind, Temperature, and Dew Point Tabulations:  
6 May 1975, SE Kansas Case

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